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Three-dimensional Cloud Visualization based on Satellite Imagery

by

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ABSTRACT

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I. INTRODUCTION

Recent advancements in computer graphics and visualization techniques allow for new and exciting ways to analyze scientific data. Today's high-performance computer graphics workstations with visualization software provide the capability for timely rendering and animation of large data sets. Scientific visualization packages are now available that allow scientists to display data sets, without requiring intimate knowledge of the software algorithms for rendering the images.

The ability to visualize clouds in 3-D, without having to mentally picture from the 2-D images, would be a great aid to weather forecasters and cloud researchers, as well as aircraft flight crews. Weather forecasters rely heavily on satellite imagery to help define the present atmospheric state, which becomes the foundation for weather prediction. Visualizing clouds in 3-D brings out features that are not readily apparent in the 2-D imagery, and thus, gives the forecaster a better picture of current conditions. In the same manner, researchers interested in studying cloud structure and formation are afforded many more viewpoints than just the "top-down" view of the satellite image. Aircrew flight preparation can also benefit by realistically visualizing

clouds along the flight path prior to takeoff. A simulated flight along the planned route, noting cloud location and height of cloud tops and bases relative to local terrain, would go far in preparing aircrews, and for that matter, meteorologists that brief aircrews.

The emergence of new scientific visualization techniques to depict and analyze multi-dimensional data will benefit meteorologists tremendously. Meteorology, in search of tools to aid in the depiction of the atmosphere, has always been a primary user of computer advancements. Remote-sensing technology, in particular, provides such large volumes of data that computer processing and enhancements are mandatory to aid human interpretation of that information. As assessed by Schiavone and Papathomas (1990), a major challenge in meteorology today is the need to optimize the human/computer visual interface in order to take advantage of the tremendous processing power of the human visual system. This optimal interface will ultimately improve the meteorology insight from complex datasets.

Visualization techniques applied to satellite imagery is of particular interest in this thesis. 3-D visualization of clouds can help meteorologists obtain a better understanding of cloud formations and structure, and ultimately improve forecasts. Previous work in this area involve perspective display techniques utilizing infrared (IR) and visible

wavelength satellite imagery (Hasler et.al., 1985 and Hibbard, 1986). In addition, work at the Naval Postgraduate School (NPS), involving 3-D cloud displays derived from IR satellite imagery (Owen, 1988), provided a starting basis for this study. Applying recent visualization developments to the previous 3-D cloud work offers improvements to prior restraints on user interactiveness, production time, and overall affordability.

Geostationary Observational Environmental Satellites (GOES) provide routine hourly visible and IR images. These 2-D images are useful for determining areal coverage of clouds and, to the trained eye, give a rough measure of cloud top location. The depth of the cloud tops is inferred by cloud brightness characteristics. The brighter the cloud appears in the IR, the colder the cloud, and thus the higher it is in a typical atmosphere. Knowing this, meteorologists can approximate cloud top heights and mentally picture the clouds in 3-D. Cloud base information can not be obtained or approximated from the satellite image, but is desired for a realistic 3-D model of clouds. Hourly surface observations provide the necessary information to derive the cloud base heights. Therefore, integration of the surface data with the satellite data, as well as surface topography data is required to build the 3-D model.

After constructing the model, a scientific visualization package is needed to render and animate the model, giving varying angles of view and simulating flight in, around and through the clouds. Several packages were reviewed to determine their applicability for the 3-D cloud model problem. One such package is Scientific Animation (SciAn), developed at Florida State University (Pepke et. al., 1990). SciAn is an interactive scientific visualization program capable of visualizing large data sets, and is flexible for user needs. More information on SciAn and the other visualization packages will be detailed in the next section.

In this thesis work, the underlying objective is to implement today's high-performance graphics workstations to visualize large meteorological datasets to better understand the phenomena that they represent. Specifically, the goal is to integrate information from satellite imagery, upper air sounding data, surface weather observations and topography data to display clouds and terrain in three dimensions. In addition, "real time" user interaction with the display should include rotation for different views, zooming for close up inspection and "fly-by" for simulating aircraft perspective. A library of cloud cases will be developed to display various cloud situations. Low lying stratus clouds off the California coast and its interaction with the coastal terrain will be studied together with stratus clouds east of the Rocky

mountains. Summertime convective cumulus clouds across the Gulf Coast states and a depiction of Hurricane Andrew as it crossed southern Florida represent more complex cases.

II. BACKGROUND

Previous 3-D cloud rendering work at NPS is described by Owen (1988). Owen modified computer graphics techniques (DEFSCT, INTCLD) developed at Colorado State University to create 3-D cloud models from GOES imagery. A general purpose software package (MOVIE.BYU) developed at Brigham Young University was used to display the 3-D cloud models. All of the software was run on a DIGITAL VAX/VMS computer system at NPS's Interactive Digital Environmental Analysis (IDEA) lab.

Owen was able to combine information from separate data sources, such as satellite imagery and sounding data, to construct constant pressure and potential temperature surfaces with clouds in three dimensional displays (Figure 1). An interesting aspect of Owen's work was the deriving of cloud base heights using a lifted condensation level (LCL) analyzed from atmospheric sounding data. This preliminary effort produced more realistic cloud descriptions rather than those produced by using an arbitrary cutoff value for the bases. However, as Owen noted, using only one sounding to determine the cloud bases throughout the whole display scene is a limitation. An improved procedure is needed to incorporate varying cloud bases and their relationship to the surface

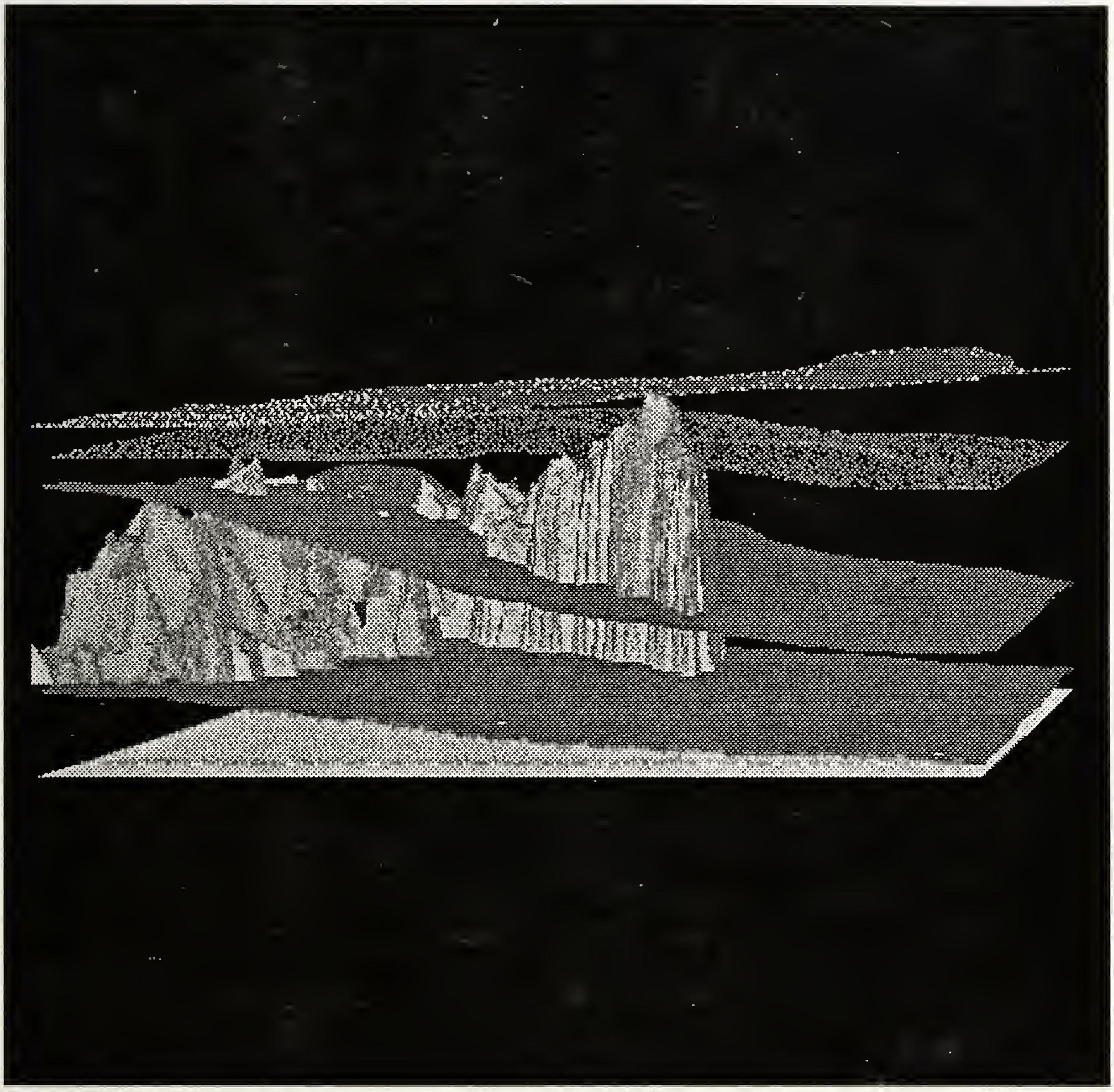


Figure 1 3–D clouds constructed from GOES IR imagery with four potential temperature surfaces: 300 K, 320 K, 340 K, 360 K (Owen, 1988).

topography throughout the scene. Figure 2 displays another example of clouds constructed in 3-D using Owen's techniques.

While Owen's work was encouraging, system memory and hardware restrictions precluded timely and efficient user interface with the display. A goal of this effort is to improve upon Owen's work by employing high-performance graphics workstations and scientific visualization packages to prepare the 3-D cloud displays. Silicon Graphics IRIS 4D workstations serve ideally for such work. Many scientific visualization packages have been developed in recent years to take advantage of the inherent graphics capabilities of these high-performance workstations.

A number of software packages, both commercial and non-commercial, have the capability to sufficiently perform the desired 3-D visualization of the cloud displays. General-purpose scientific visualization packages such as the IRIS Explorer from Silicon Graphics, provide excellent visualizations on the Silicon Graphics machines. However, a problem with these types of packages is, due to their general-purpose nature, the user needs to build networks of processes to get images on the screen. While attempting to narrow the field of prospective packages to use for the 3-D cloud problem, the focus turned toward visualization packages that have been developed for environmental data. Noncommercial packages such as VIS-5D and the previously mentioned SciAn,

(a)

(b)

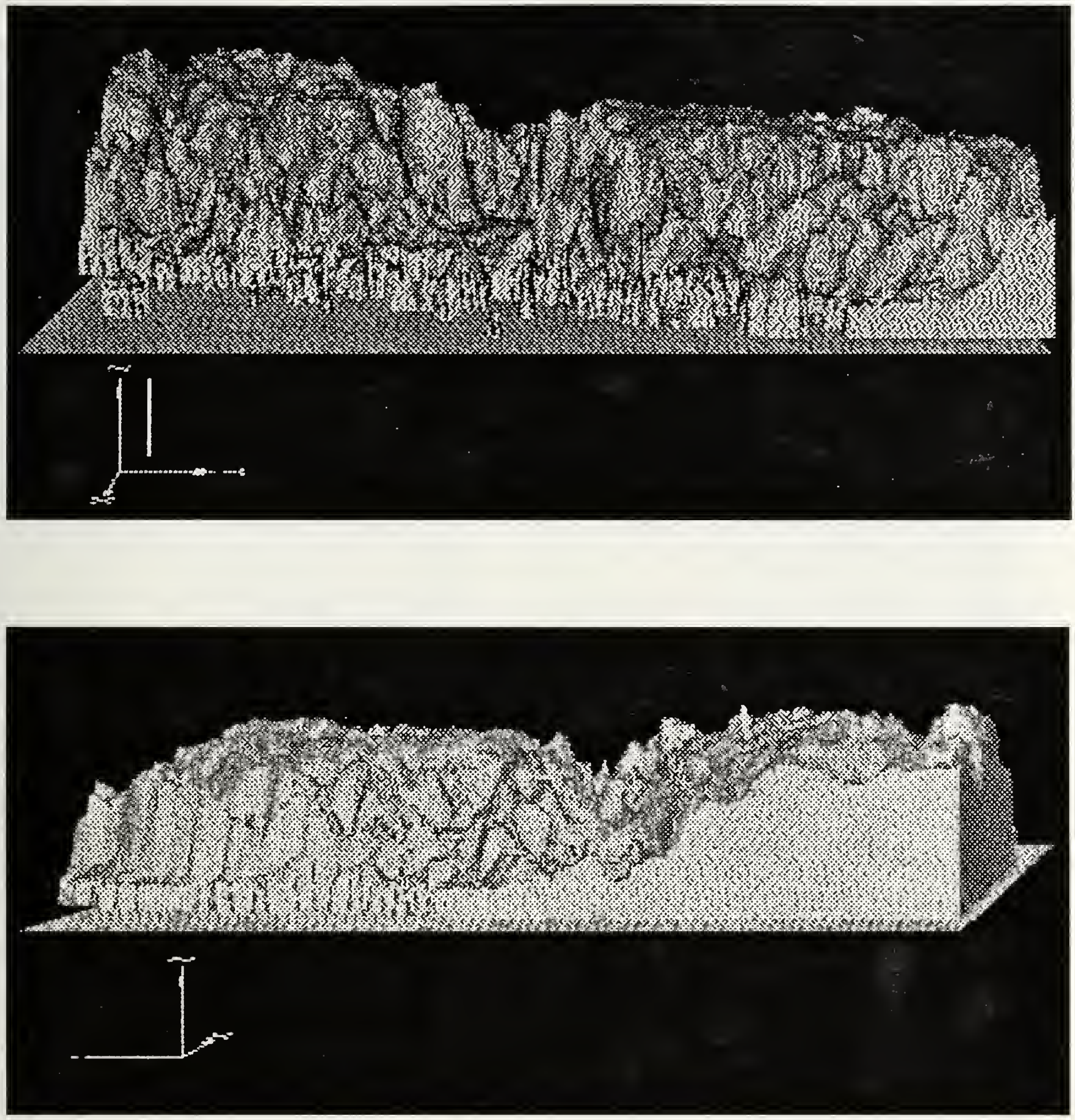


Figure 2 View from the north (a) and from the south (b) of a 3–D cloud display constructed from GOES IR imagery using techniques described by Owen.

provide the necessary capabilities without the price of more polished commercial packages.

VIS-5D (Figure 3), developed at the University of Wisconsin is a popular visualization package in the scientific visualization community at NPS. VIS-5D is currently being used to visualize meteorological and oceanographic numerical model data over hemispheric scales. As described by Hibbard and Santek (1991):

> VIS-5D allows for visualizing large data sets created by numerical weather models and similar sources, by working on the data in the form of a five-dimensional gridded rectangle. The data are real numbers at each point of a grid which spans three space dimensions, one time dimension and a dimension for enumerating multiple physical variables.

VIS-5D is a capable package, with emphasis on visualization and time series animation of numerical model data on a hemispheric scale.

The more appropriate package for this thesis work with 3-D cloud construction was SciAn. "SciAn is an interactive scientific visualization program which was developed to meet the needs of the Supercomputer Computations Research Institute (SCRI) at FSU" (Pepke, et. al. 1991). SciAn (Figure 4) possesses unique capabilities such as variable lighting schemes and a flight simulator "Observer" allowing for "fly-by" inspection of mesoscale data displays. The decision to use the SciAn package was made due to its ease of use, unique

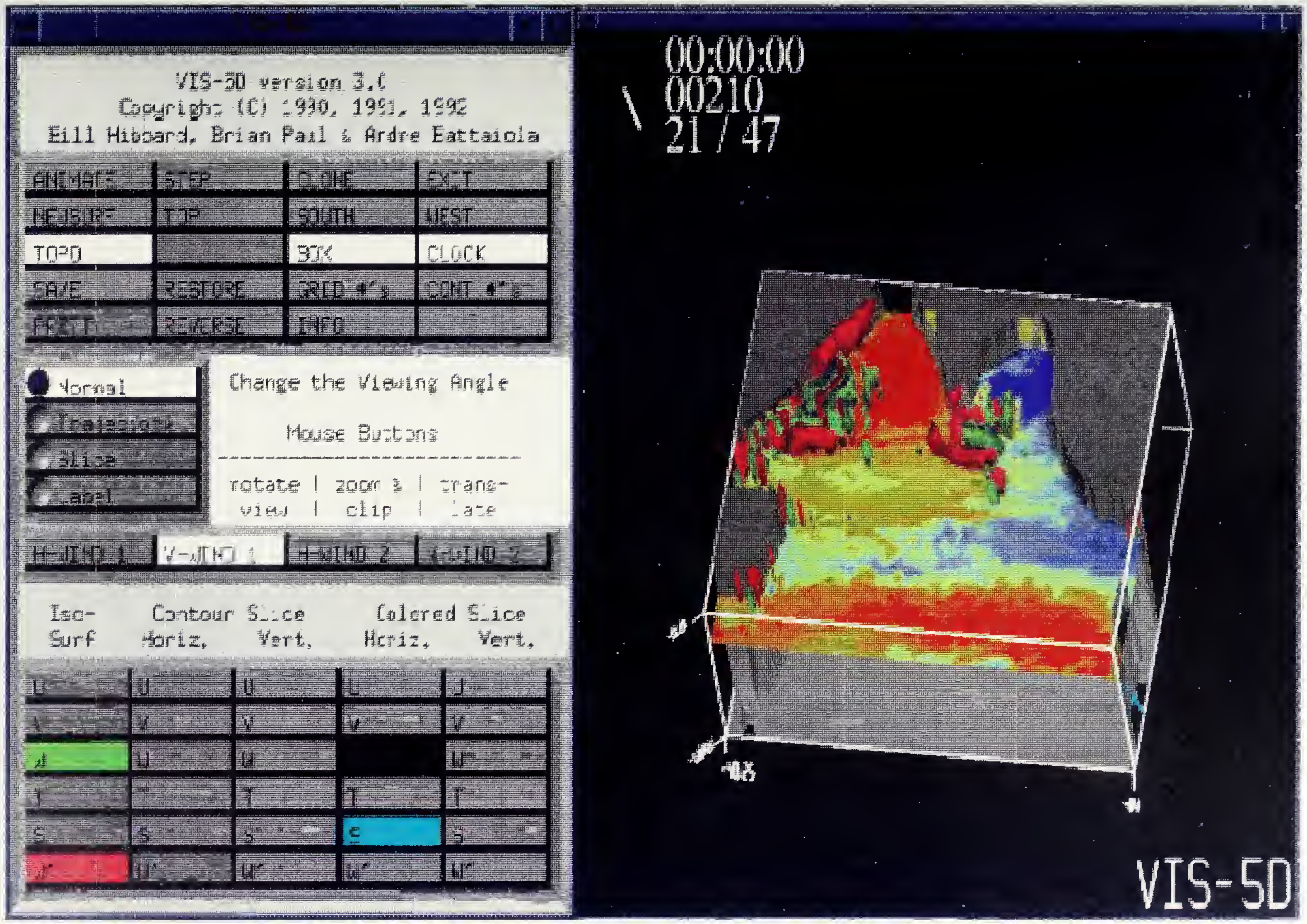


Figure 3 VIS–5D visualization window displaying oceanic numerical model data for Indian Ocean region.

Figure 4 SciAn visualization window displaying Doppler radar data.

visualization capabilities and overall flexible user interface.

SciAn, still under development, is designed as an object-oriented graphics program. User interface is mouse driven, incorporating "point and click" icons and system window operations. SciAn contains a variety of file readers, which are used to input data sets in the form of data files. Each file reader expects to read the input data file in a certain format. The user must ensure the data file is in the correct format and has the appropriate file extension for the desired file reader. Multiple files, with the same or differing formats, may be displayed simultaneously. These files may represent a variety of data sets including 2-D scaler fields, such as terrain elevation data, and 3-D scaler fields, such as atmospheric thermodynamic variables. For the 3-D cloud applications, one data file will contain the cloud illumination characteristics at different points in a 3-D field. Another data file will contain the 2-D surface elevation data which will be displayed under the clouds. After using the file readers to enter the data, SciAn can visualize one or multiple "opened" data files. A brief overview of the visualization process as explained by SciAn's authors, Pepke et al. (1990), as follows:

> The process of using SciAn to develop a visualization is one of progressive refinement. SciAn uses defaults and heuristics to make it easy to bring a visualization up on

> the screen. Once there is an image to work with, the visualization is refined using tools that emphasize breadth and flexibility.

By adjusting such tools as coloring, lighting, surface texture and size scaling the user can create desired effects and enhance features of particular interest. With the use of mouse controls, the user can manipulate the viewing angle, image placement in the window and rotation about an axis. The "Observer" tool allows for zooming the perspective in and out, and for the previously mentioned flight simulation to investigate the image up close.

SciAn provides a script feature that can remember the functions performed during a particular session. The script is saved as a text file that may be modified or run "as is" if the same exact job is desired again. This is an exceptionally valuable tool when creating multiple frames for a movie production. While SciAn does provide animation of objects in terms of rotation and perspective viewing changes, animating in time is only accomplished by saving images to file for playback on other sources (i.e. digital video equipment). The pictures or frames may be saved to files in Silicon Graphics standard image format (.rgb). Another helpful feature for video production is a text editor, providing multiple fonts and type sizes that can be displayed alone or along with the rendered image.

III. PROCEDURE

Three main steps need to be taken to visualize the cloud scenes. Procedures were modified and/or developed to retrieve and prepare the data into the correct format for the visualization software to read. Appendix A includes a list of all the programs needed for each step in the retrieval, preparation and visualization process.

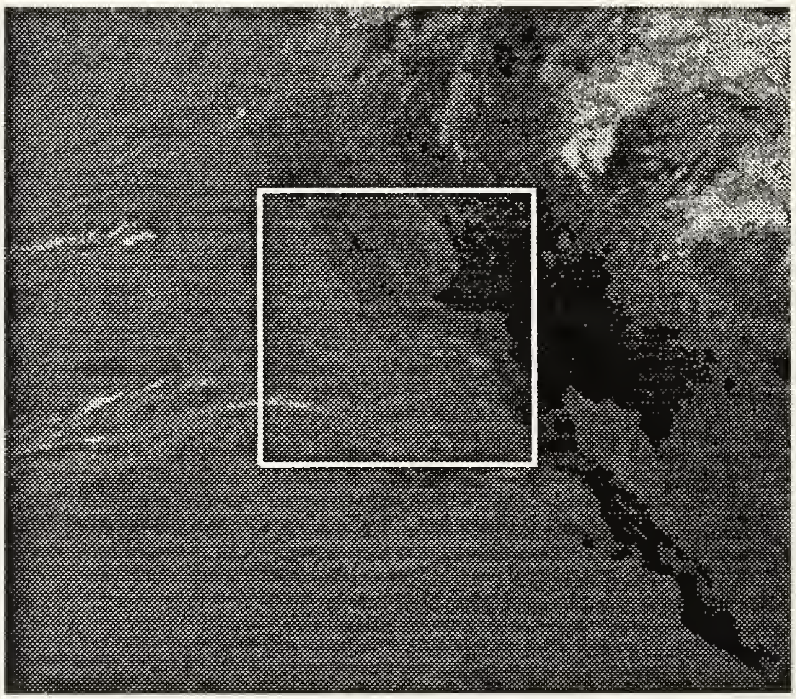
A. DATA RETRIEVAL

The initial procedure involves collecting the necessary data from a variety of sources, including satellite imagery, upper-air sounding, surface weather observations and surface topography data. The satellite imagery is retrieved using the IDEA lab VAX/VMS system. Routines on the SGI workstation are utilized to acquire the remaining data necessary for constructing the 3-D display of the area of interest.

1. Satellite imagery

GOES satellite imagery is received routinely at NPS on an hourly basis, providing an easily accessible data base. The IDEA lab is used to load IR and visible images (Figure 5) onto a graphics display. The images are navigated to allow latitude and longitude determination for a given location on the image. An area of interest is selected and designated by

(a)



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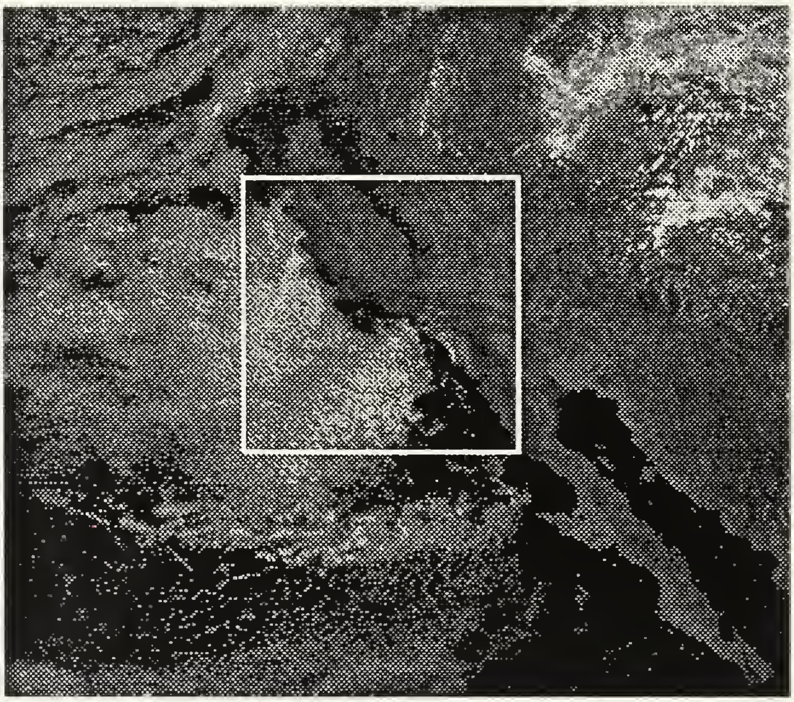


Figure 5 Sectors of GOES IR (a) and visible (b) images covering the western U.S. at 1801 UTC 31 August 1992. Area to be displayed in 3–D indicated by box.

a rectangular box, as depicted in Figure 5. The latitude/longitude location of the four box corners and center are determined as well as the ground level distance (km) covered by the box's width and height. The IR image is processed to extract the brightness counts for each pixel within the desired box of the IR image. The brightness counts are converted to corresponding temperature (K) values using the standard IR calibration table (Clark, 1983) and output to a data file. Transferring the IR temperatures data file to the SGI workstation concludes the use of the VAX/VMS system.

2. Upper-air Sounding Data

GEMPAK, which was developed at the NASA/GSFC (desJardins and Petersen, 1986), is used to retrieve representative upper air sounding data. For this thesis work, one sounding is used to represent the atmosphere structure for the entire area of interest. As Owen (1988) observed, this is a restrictive assumption, as the vertical structure of the atmosphere varies substantially over the mesoscale region that comprises the area of interest. Numerical Weather Prediction (NWP) analysis grid point temperature profiles could be used in the future to describe cases with varying atmospheric structure. For this work, one sounding from near the center of the area of interest gives an approximate indication of the vertical structure of the atmosphere over the area of interest. It is used to convert cloud top IR temperatures to

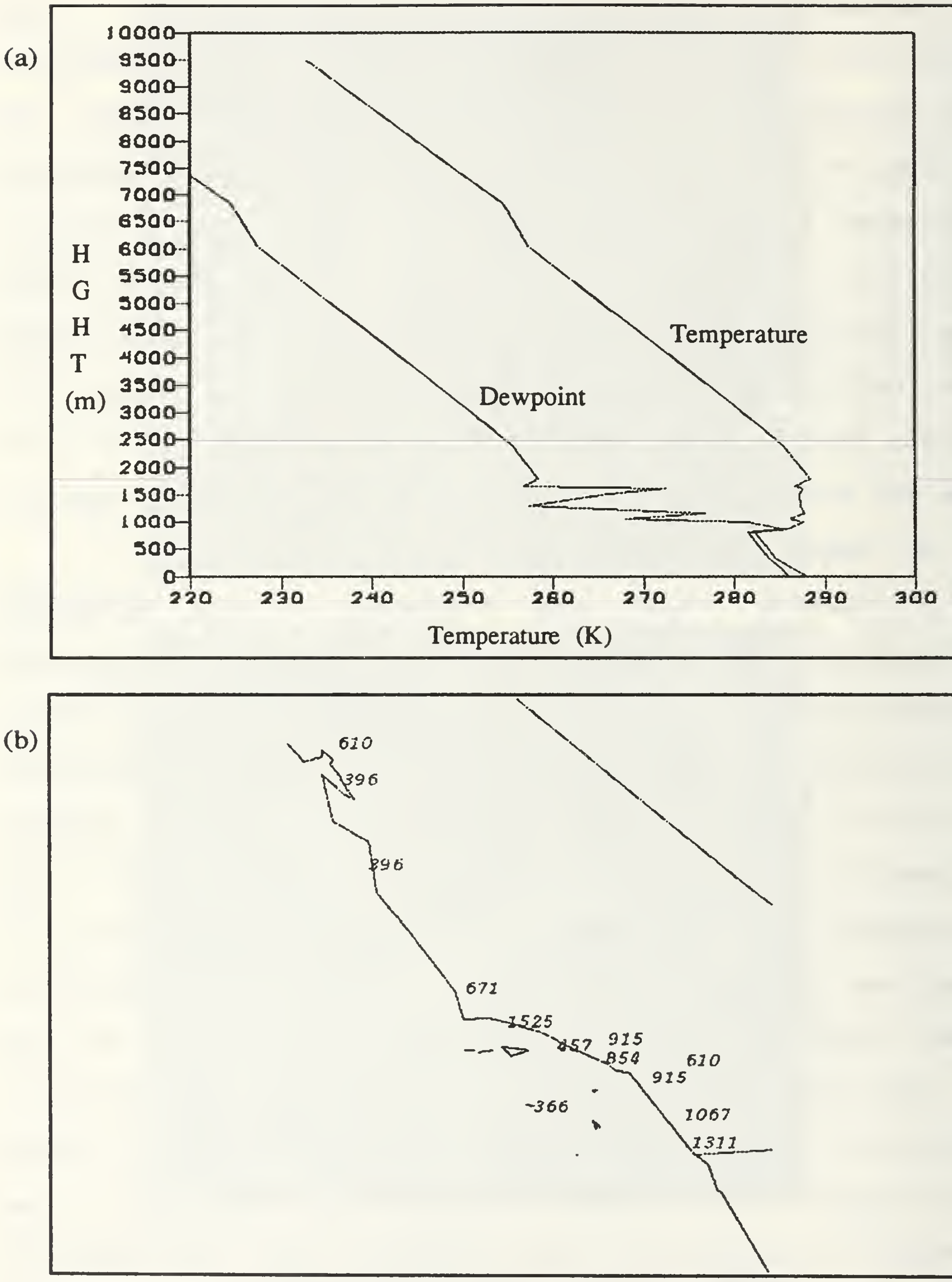


Figure 6 GEMPAK plots of Oakland sounding data at 1200 UTC 31 August 1992 (
and observed low cloud bases (m) at 1800 UTC 31 August 1992 (b).

heights above the surface. Sounding data used for the stratus over ocean case is displayed in Figure 6a.

3. Surface Observations

GEMPAK is also used to provide a gridded data set of surface observations over the area of interest (Figure 6b). In particular, surface dewpoint depressions and observed cloud base heights are objectively analyzed to grids that approximately represent the pixel grid locations from the satellite image. An approximation arises due to the GOES projection of the satellite image. The pixel box coordinates do not follow lines of constant latitude and longitude, where as the GEMPAK grid is bound by constant latitude and longitude lines. The two grids differ to a varying degree depending on location with respect to the satellite location.

4. Surface Topography Data

Worldwide surface topography data (ETOPO5) from NOAA's National Geophysical Data Center, with 5 minute grid resolution (12 points per degree latitude and longitude), was used for terrain. Data values, given to the nearest whole meter, are positive for above sea level and negative for below. The data is retrieved for the pixel box coordinates. The same problem of grid differences arises with the surface topography data. However, the retrieval of the data can be adjusted so that the grid coordinates correspond to the satellite pixel grid coordinates. A matching scheme and

linear interpolation are performed to convert the surface topography information to the grid points of each pixel of the area of interest.

B. DATA PREPARATION

After the data is retrieved, the data needs to be converted into an acceptable format for SciAn to read. SciAn recognizes a variety of file formats for the data input files. The file formats selected for the 3-D cloud data (kj1) and the 2-D terrain data (kj2) require the data to be entered as ASCII floating point numbers in array format. A program was developed to construct the cloud and terrain data arrays in the kj1 and kj2 formats for SciAn to read. A header has to be constructed for each data file in order that SciAn understands how the data is set up. Origin location of each dimension, distance between each point in each direction, and number of points in each dimension all need to be included in the header of the file.

The 3-D clouds are constructed by first initializing a 3-D data array to null (no cloud) values. The 3-D array can be conceptualized as a big cube which is sectioned into many evenly dimensioned small cubes. Cloud top heights are determined by converting the IR temperature data to cloud top height data as described by the algorithm in Figure 7. The data array points at and below the cloud top heights are set to values equal to the height (km) of that level and indicate

Convert IR tempertures to cloud top heights (CTH),
for each pixel location:

1. Is IR temp > the max snd temp?
   YES – CTH is set to 0 (sfc). STOP.
   NO – Proceed to step 2.

2. Is IR temp $\leq$ the TOP snd level temp?
   YES – CTH is set to TOP level height. STOP.
   NO – Proceed to step 3.

3. Set current snd level to the BOTTOM + 1.

4. Is (current snd level) temp $\geq$ (current snd level –1) temp?
   YES – Go to step 5a.
   NO – Go to step 5b.

5.a. Is IR temp < (current snd level) temp AND
   is IR temp > (current snd level – 1) temp ?
   YES – CTH is linearly interpolated between current level and level below. STOP.
   NO – Increment current sounding level to next level up and go back to start of step 4.

5. b. Is IR temp $\geq$ current snd level temp?
   YES – CTH is linearly interpolated between current level and level below. STOP.
   NO – Increment current sounding level to next level up and go back to start of step 4.

Figure 7 Algorithm for converting IR temperatures to cloud top heights.

cloud is present at that particular location. For cumulus clouds, the values beneath the cloud top heights are randomly set to null (no cloud) values. This is done to avoid the cumulus clouds from appearing as column-like structures. The next step is to input the observed cloud base. Values at the points in the data array below the cloud base height are returned to null.

The terrain file is set up as a 2-D data array of X and Y points covering the area of interest, with the value of the surface elevation above sea level at each array point. For locations below sea level (i.e. oceans) the negative values are scaled by 1/1000 so that the ocean surface will be rendered rather than the ocean floor.

The solar zenith and azimuth angles are calculated for the center point of the area of interest, and output to a data file. The solar angles are not among the initial input to SciAn, but the user can manually adjust the visualization lighting to correspond to the solar angles.

C. DATA VISUALIZATION

After the data has been prepared, SciAn is implemented to visualize the data. SciAn uses file readers to open the data files and input the data sets. After the files are input, the user can choose to visualize one or more of the data sets. To visualize a data set, SciAn uses default values to render an initial picture (Figure 8). The user can then refine the

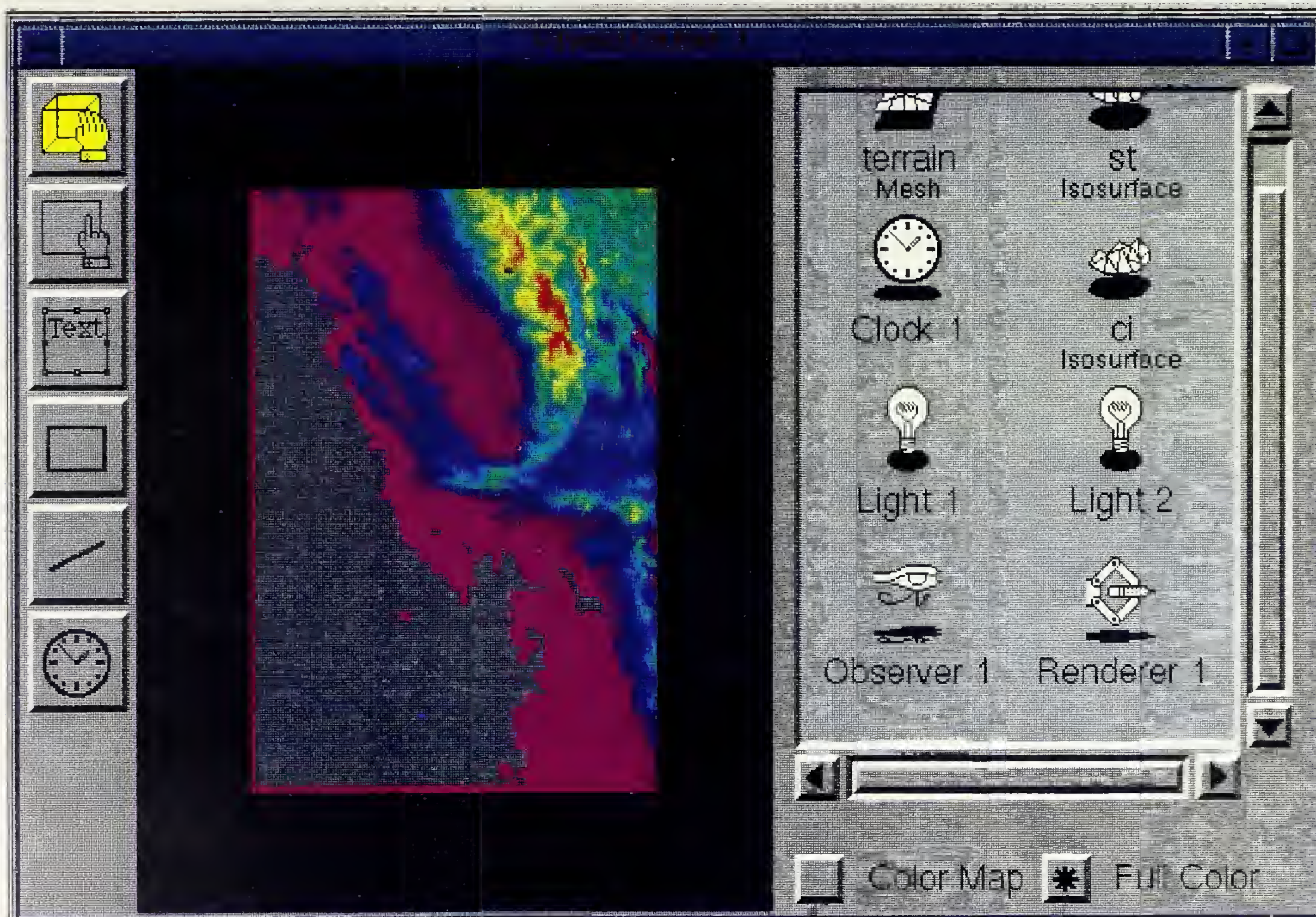


Figure 8 SciAn initial 3–D rendering of cloud scene viewed from above.

visualization by adjusting the level of display parameters (Figure 9). Once the visualization is set up as desired by the user, the display can be manipulated to show different views of the data. The display can be rotated on any axis, zoomed in on to get a closer look, and flown through using the "Observer" tool.

Figure 9 SciAn user adjusted 3–D rendering of cloud scene viewed from above.

IV. RESULTS

Four separate cloud case scenes were constructed to demonstrate the usefulness of visualizing and interacting with cloud scenes in three dimensions. In this chapter, sounding and surface data, GOES IR and visible images and two three-dimensional renderings are presented for each cloud case. The cloud scenes are constructed without using information from the visible imagery. Comparing the rendered cloud scene to the visible image will help verify the 3-D constructed cloud scenes. Real time interactions with the cloud scenes have been recorded onto video tape which is available if interested (Appendix B).

A. STRATUS OVER OCEAN

The first case involves the low stratus clouds off the California coast during the morning of 31 August 1992. The Oakland sounding data at 1200 UTC that morning (Figure 6a) indicates a strong inversion with stratus clouds based near the surface and having tops near 1000 m. The atmosphere above 1000 m was dry, with no indication of clouds. When stratus is present, there is usually a significant low level inversion. This creates a problem with the temperature relationship with height. A temperature value that falls within the inversion

area (282 to 288 K in Figure 6a) can correspond to more than one height value. The algorithm for converting IR temperature to cloud top height (Figure 7) handles situations where one strong inversion is present. The cloud top temperature search is started from the bottom for the stratus cases, so the lower cloud top height is chosen. If more than one inversion is present, that case may not work. A plot of surface observations at 1800 UTC 31 August 1992 (Figure 6b) shows low cloud bases of 396 m over Oakland and the Monterey area and as low as 366 m over San Nicholas Island, CA. Cloud bases over southern California range from 600 to 1500 m.

Sectors of GOES IR and visible images at 1801 UTC 31 August 1992 covering the western U.S. are displayed in Figure 5. A box outlines the area of interest along the California coastline in each image. Figure 10 shows enlarged views of the boxed region from the GOES IR and visible imagery from Figure 5. The enlarged IR image (Figure 10a) indicates that the stratus cloud tops over the ocean have temperatures of a mostly uniform distribution, except for the lower left box corner where a band of brighter (colder) clouds is evident. Within the boxed area on the visible image (Figure 10b), low clouds are observed in the upper left corner of the box (along the northern California coastline from the San Francisco Bay and southward along the central coast). Near the center of the box (southern California) a gap appears between the coast

(a)

(b)

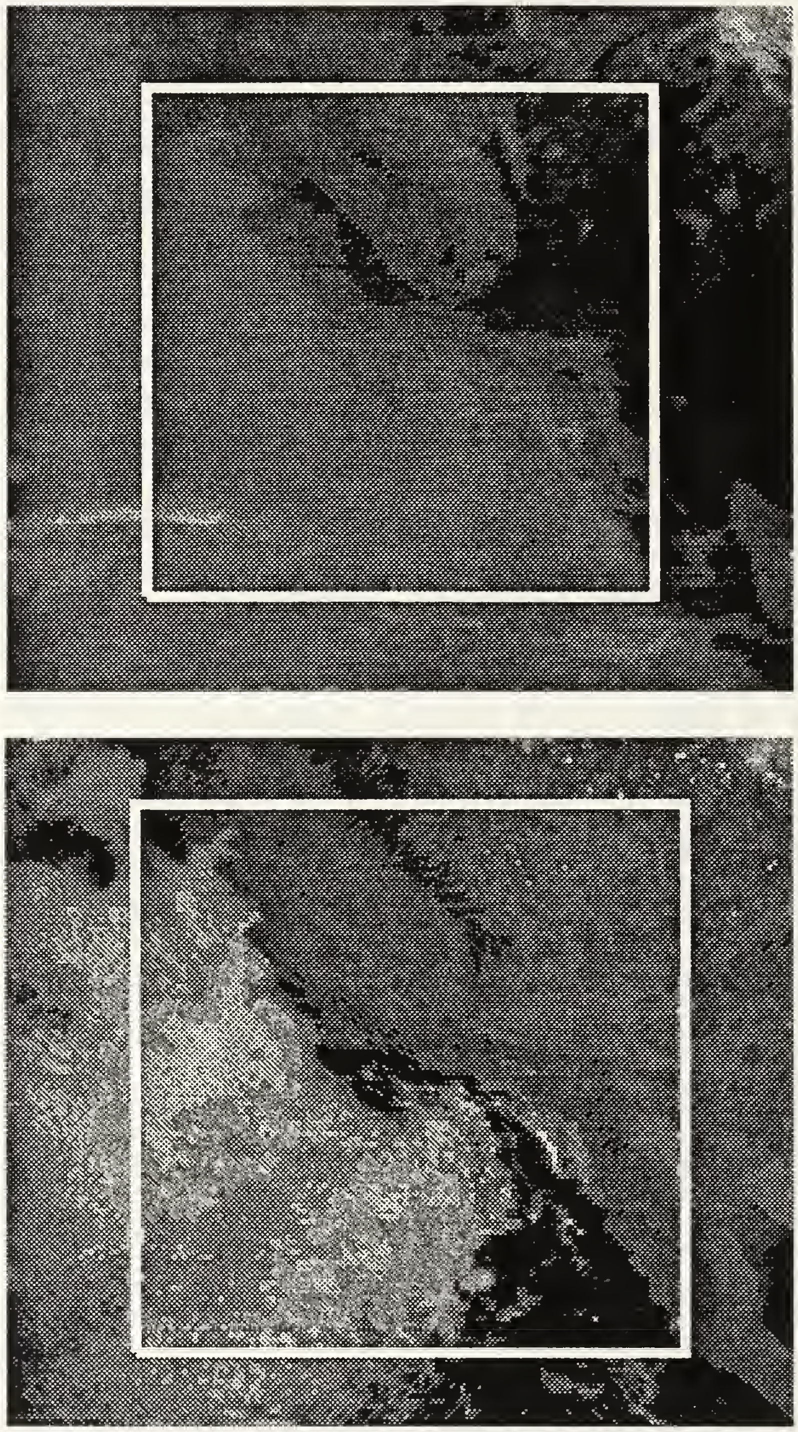


Figure 10 Enlarged views of the GOES IR (a) and visible (b) subimages of the California coastline at 1801 UTC 31 August 1992. Area to be displayed in 3–D indicated by box.

and the stratus to the south. A band of low clouds is indicated over the coastal area in the lower right box corner (near San Diego). In the upper right corner (over the southern Sierra Mountains) a few scattered clouds are seen.

The three dimensional rendering of this cloud scene (Figure 11) displays the area of interest as a rectangle instead of as a square as in the satellite images. This transformation occurs due to the conversion from the satellite projection of the Earth to a flat surface projection. The X direction distance is 627 km and the Y direction distance is 935 km. The upper left and lower right corners of the box are areas where the land is meeting the ocean, as is the case with the boxed area in the satellite image. In the northeast quadrant of the rendering (southern Sierra Mountains), several isolated clouds are noted as they were in the visible image. A distinctive hook feature is evident in the northwest quadrant (over San Francisco Bay) in both the 3-D rendering and in the visible image. Most of the eastern Pacific Ocean in the area of interest is covered by low stratus clouds of which the edges are seen hugging the northern and central California coast. Near the area's center (southern California coast) the ocean surface can be seen, as a significant gap appears between the coast and the stratus. The low clouds break up and a clear area is evident in the southeast quadrant of both the rendering and the visible image (southwest of San Diego).

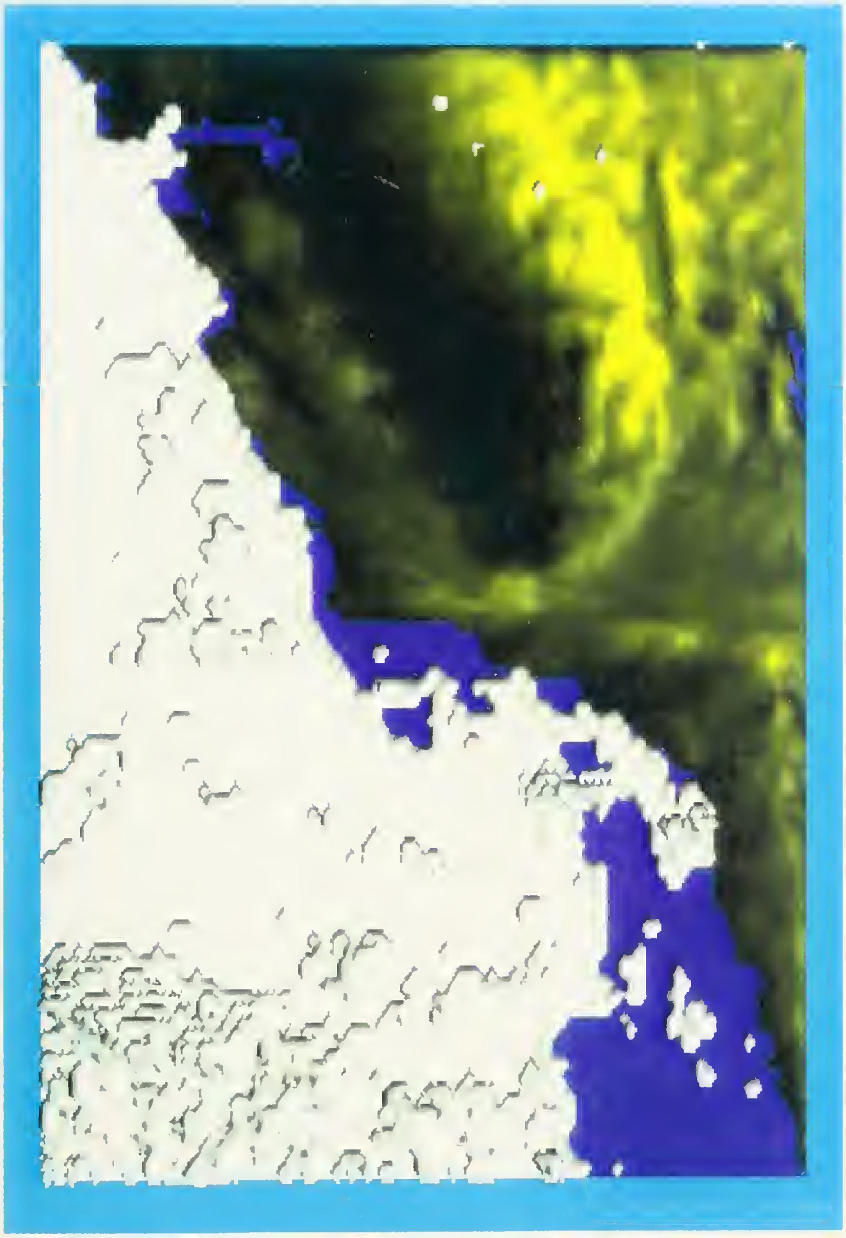


Figure 11 View from above of 3–D rendering of cloud scene off California coast on 31 August 1992.

Two areas of higher clouds appear over the southern California coast in the 3-D rendering and are evident in the visible image as well. The surface observations (Figure 6b) indicate bases close to 1000 m for these clouds. Other clouds at this elevation are seen sporadically over the stratus clouds, and a band of even higher clouds appears in the bottom left corner of the box. These clouds are hard to distinguish on the visible image, but are very apparent in the IR image. Overall, the 3-D rendering of the stratus cloud scene off the California coast closely resembles the cloud patterns seen in the visible and IR images.

After the cloud scene has been rendered, SciAn allows the user to interact with the display. Figure 12 shows a different view of the stratus off California after simple vertical and horizontal rotations were performed to the display. Rotation about any axis, zoom transformation and flight simulation are excellent tools to access and investigate the cloud scene in an almost life-like environment. With these new perspectives, the vertical structure of the scene becomes much more apparent. The observer no longer has to imagine the height and depth of the clouds.

B. STRATUS OVER LAND

The second case depicts low stratus clouds over the Great Plains states, as well as higher clouds above the stratus and

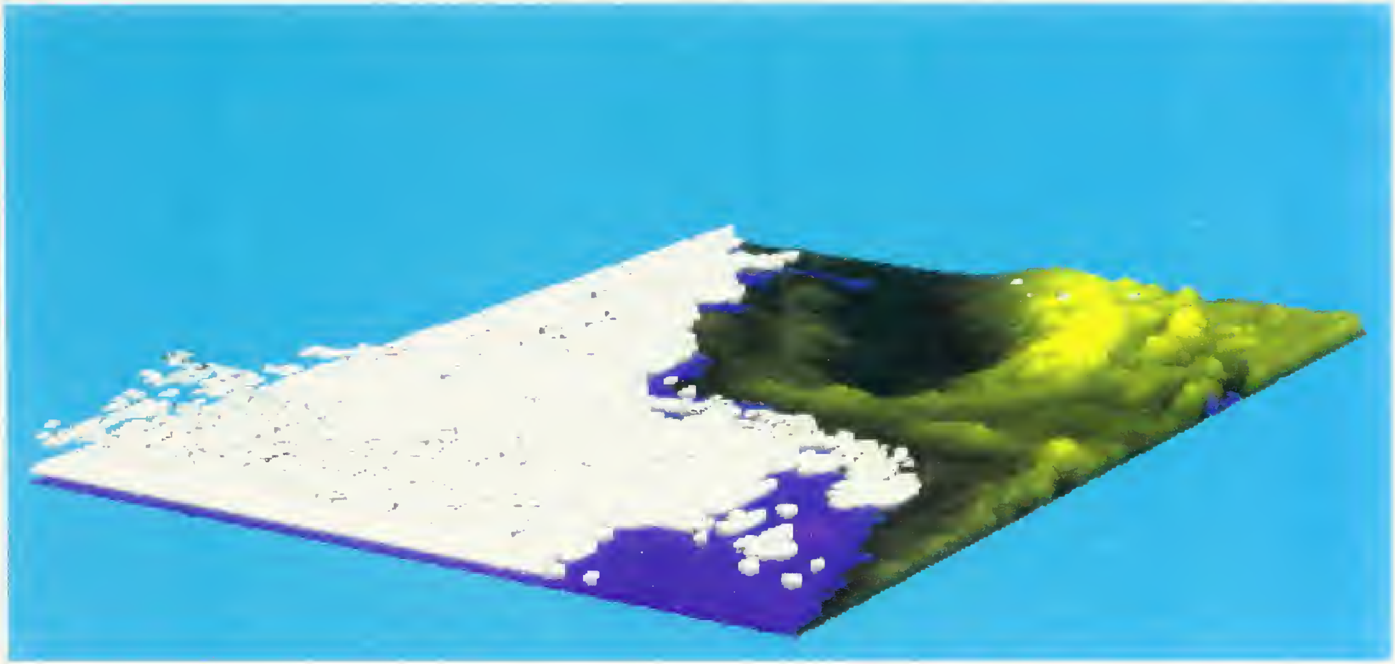


Figure 12 Tilted view from the southeast of 3–D rendering of cloud scene off California coast on 31 August 1992.

over the Rocky Mountains during late afternoon on 30 October 1992. The Dodge City sounding data at 0000 UTC 31 October 1992 (Figure 13a) indicates low clouds with bases near the surface and tops near 2000 m. A very dry layer is shown above the stratus up to 6500 m where a higher cloud layer is indicated through 7500 m. A strong low level temperature inversion is present as in the first stratus case. If another inversion was present, this case would not have been attempted. A plot of observed low cloud bases at 2200 UTC 30 October 1992 (Figure 13b) shows the bases across western Kansas and southwestern Nebraska varying 200 to 400 m above the surface. Low cloud bases over Colorado and New Mexico are mostly over 1500 m above the surface.

Figure 14 displays sectors of GOES IR and visible images covering the central U.S at 2201 UTC 30 October 1992. The boxed area of interest encompasses the eastern parts of Colorado and New Mexico and the western parts of southern Nebraska, Kansas, Oklahoma and Texas. Figure 15 shows enlarged views of the area of interest from the images in Figure 14. The IR image (Figure 15a) indicates high clouds with varying cloud tops in the upper left portion of the box (over the Rocky Mountains). High clouds over low clouds are indicated in the upper right portion of the box (Great Plains region). Two main bands of high clouds are observed stretching from the northwest quadrant towards the center of

(a)

(b)

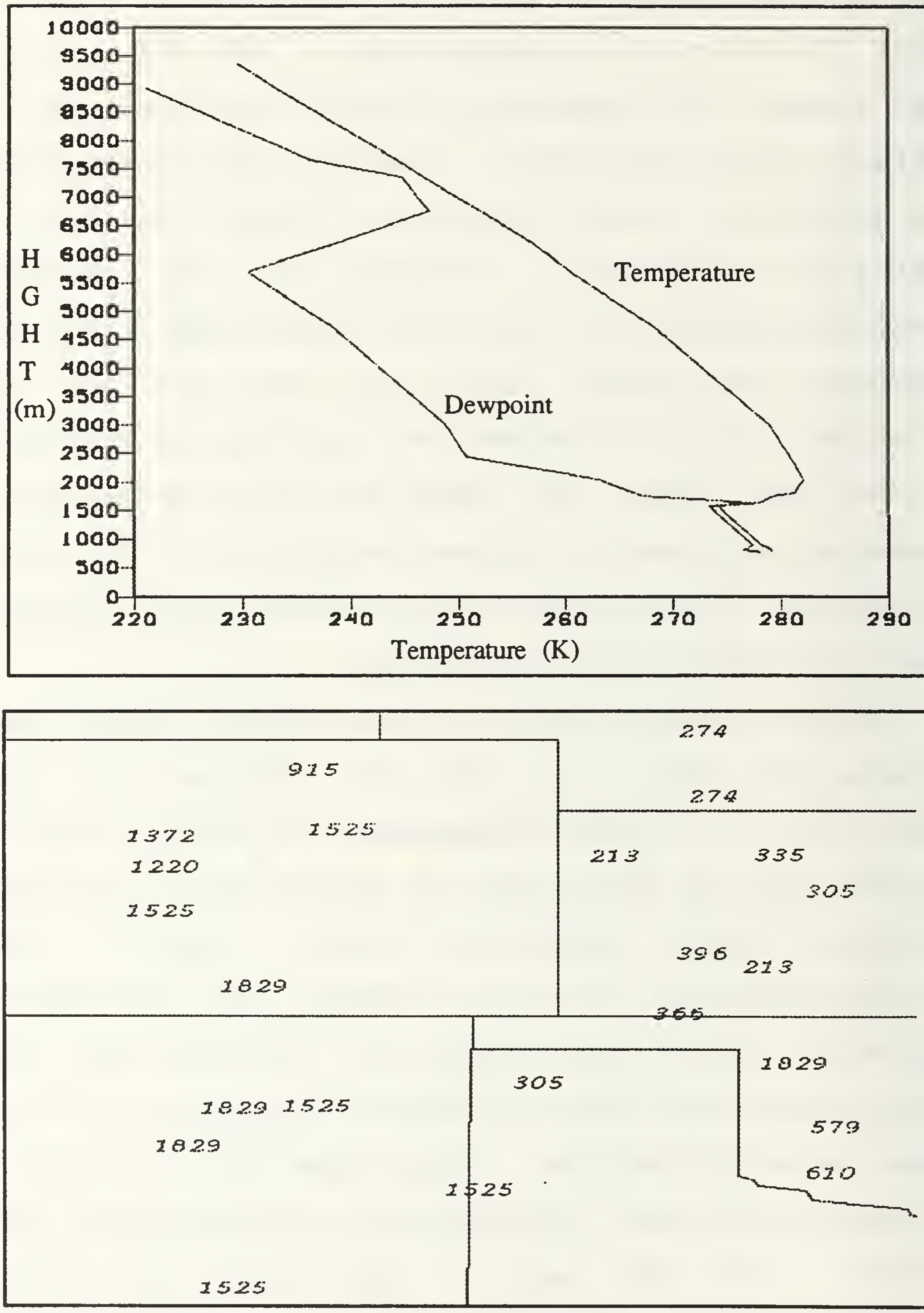


Figure 13 GEMPAK plots of Dodge City sounding data at 0000 UTC 31 October 1992 (a) and observed low cloud bases (m) at 2200 UTC 30 October 1992 (b).

(a)

(b)

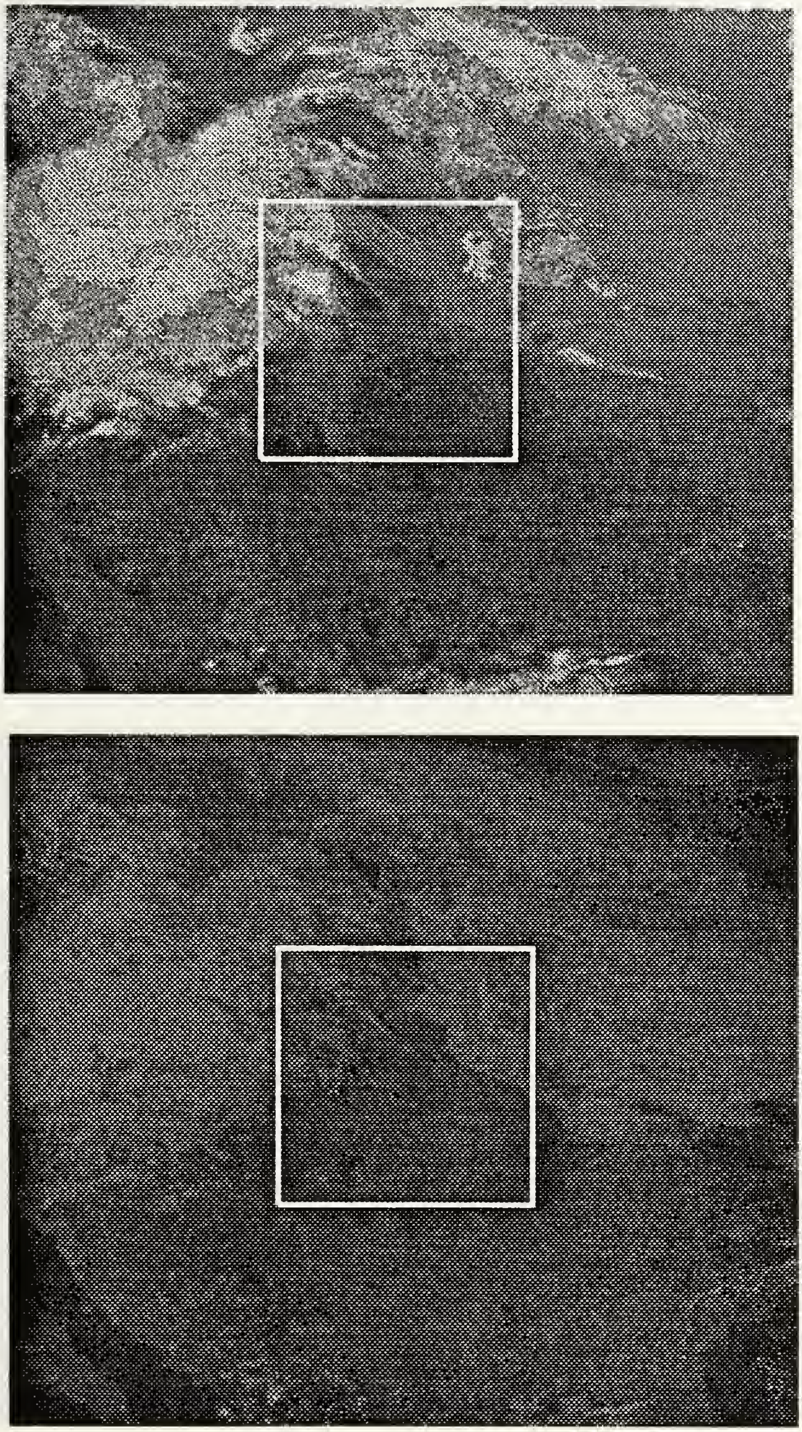


Figure 14 Sectors of GOES IR (a) and visible (b) images covering the central U.S. at 2201 UTC 30 October 1992. Area to be displayed in 3–D indicated by box.

(a)

(b)

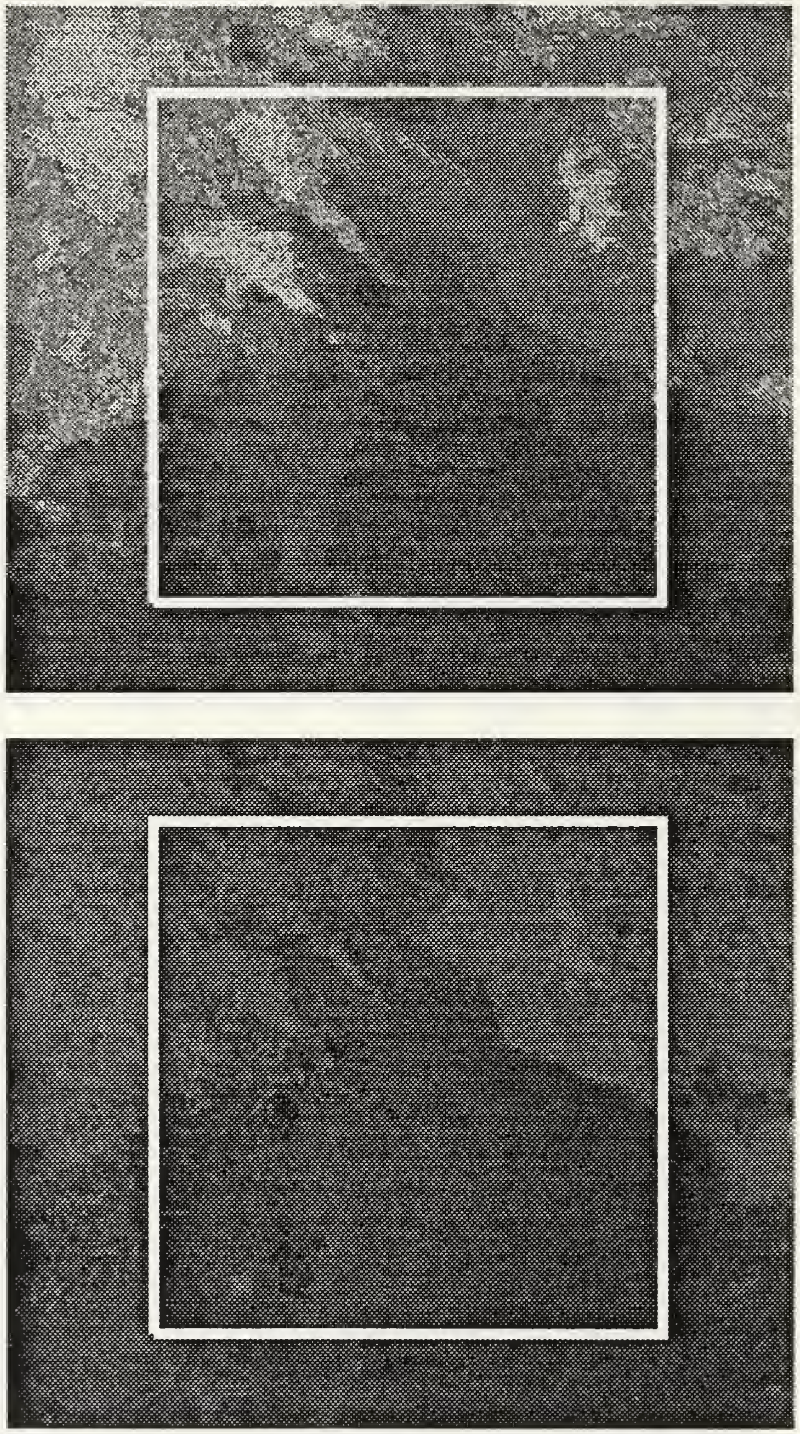


Figure 15 Enlarged views of the GOES IR (a) and visible (b) subimages covering the eastern Rocky Mountains and western Great Plains at 2201 UTC 30 October 1992. Area to be displayed in 3–D indicated by box.

the image. The visible image (Figure 15b) shows a sharp delineation between low stratus clouds in the northeast quadrant and no cloud in the central to southern portions of the box. High clouds over the stratus are evident as is the high cloudiness over the Rockies.

The 3-D rendering of this cloud case (Figure 16) is displayed with an X direction distance of 632 km and a Y direction distance of 982 km. The scene includes the relatively flat terrain across the eastern half of the depicted area (the Great Plains) and mountainous terrain across the western most portion (the Rocky Mountains). The stratus in the northeast quadrant creates a sharp boundary with the no cloud region to the southwest. This boundary follows the same curvature noted in the visible and IR images. High clouds are displayed above the northern and eastern portions of the stratus. High clouds with varying cloud top heights are displayed over the terrain in the northwest quadrant of the image (the Colorado Rockies). Northwest to southeast banding of high clouds is evident in the 3-D rendering and corresponds well to the banding locations in the satellite images. Isolated cloud elements are observed across the western edge of the southwest quadrant of the image, and are evident in the visible image.

Figure 17 displays the cloud scene from a different perspective. Rotations and zooming were performed to maneuver

Figure 16 View from above of 3–D rendering of cloud scene over eastern Rocky Mountains and western Great Plains on 30 October 1992.

Figure 17 Tilted view from the south of 3–D rendering of cloud scene over eastern Rocky Mountains and western Great Plains on 30 October 1992.

the viewing eye close to ground level over the southeast portion of the scene (northern Texas). The flat terrain of the Great Plains is evident in most of the image. Low stratus clouds with uniform tops appear over the flat terrain. To the west, the rugged terrain of the Rocky Mountains is indicated. Multiple clouds with varying cloud tops are evident to the northeast over the low stratus, and to the northwest over the Rockies.

C. CUMULUS

The third case depicts convective cumulus clouds over the Gulf Coast region during late afternoon of 3 September 1992. The sounding data from Tallahassee at 0000 UTC 4 September 1992 (Figure 18a) indicates a moist environment from the surface to seven km. Below 15 km, the temperature retains a positive lapse rate which simplifies the IR temperature to height conversion. Iribane and Godson (1981) derived an approximation (Eq 1) of the lifted condensation level (LCL). In a convective environment, given the surface dewpoint depression, the LCL (m) over a particular location can be approximated using Eq 1.

$$LCL \approx 120.0 * (T-T_d) \tag{1}$$

LCL values calculated using the above approximation are displayed in Figure 18b. A low value of 267 m was calculated

(a)

(b)

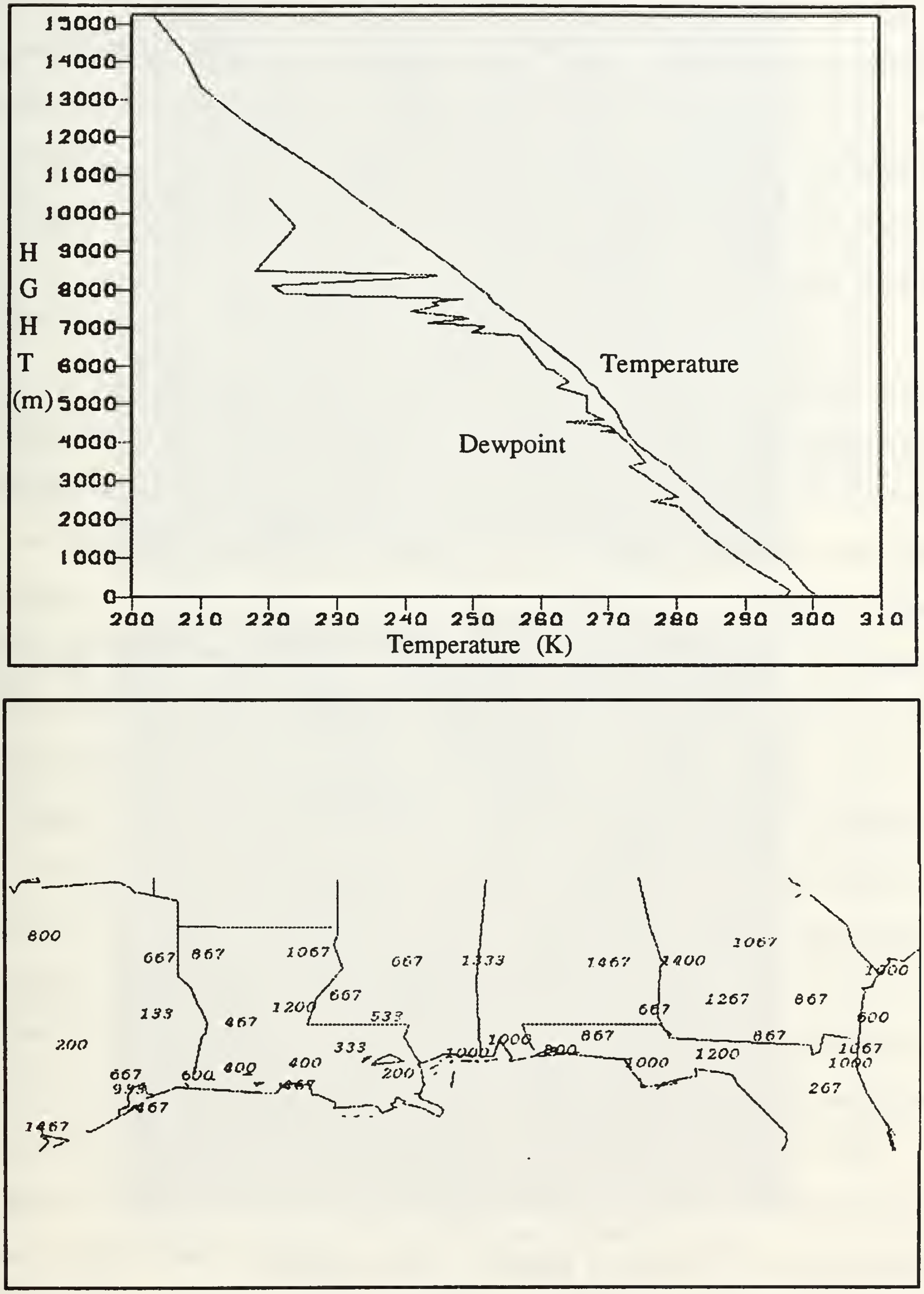


Figure 18 GEMPAK plots of Tallahassee sounding data at 0000 UTC 4 September 1992 (a) and LCL values (m) derived from surface dewpoint depressions at 2100 UTC 3 September 1992 (b).

over northern Florida, near Jacksonville. Over the Florida panhandle the LCL values increase to near 1000 m, decrease to as low as 200 m over Louisiana, and increase gradually westward. For the regions where active convection is occurring, the LCL approximation compares very well to observed cloud bases.

Sectors of the GOES IR (Figure 19a) and visible (Figure 19b) images covering the southeast U.S. at 2101 UTC 3 September 92 include an area of interest along the coastline. The area of interest has to be defined by a boxed rectangle, but as in this case, an elongated rectangle can define the area instead of a square as in the other cases. Enlarged views of the boxed area from Figure 19 are displayed in Figure 20. A small portion of a large thunderstorm cell is evident in the lower right corner of the box (northern Florida). Convective cumulus cells are indicated across the right half of the box (Florida panhandle, Georgia and Alabama) with isolated small cumulus to the south. The box's bottom boundary cuts through a large thunderstorm cell south of Louisiana. The box's left boundary is just to the west of another large thunderstorm over eastern Texas.

The 3-D rendering of the cumulus cloud scene (Figure 21) is displayed with an X direction distance of 1406 km and a Y direction distance of 458 km. The extreme lower right corner shows a small portion of what was a big cloud mass just

(a)

(b)

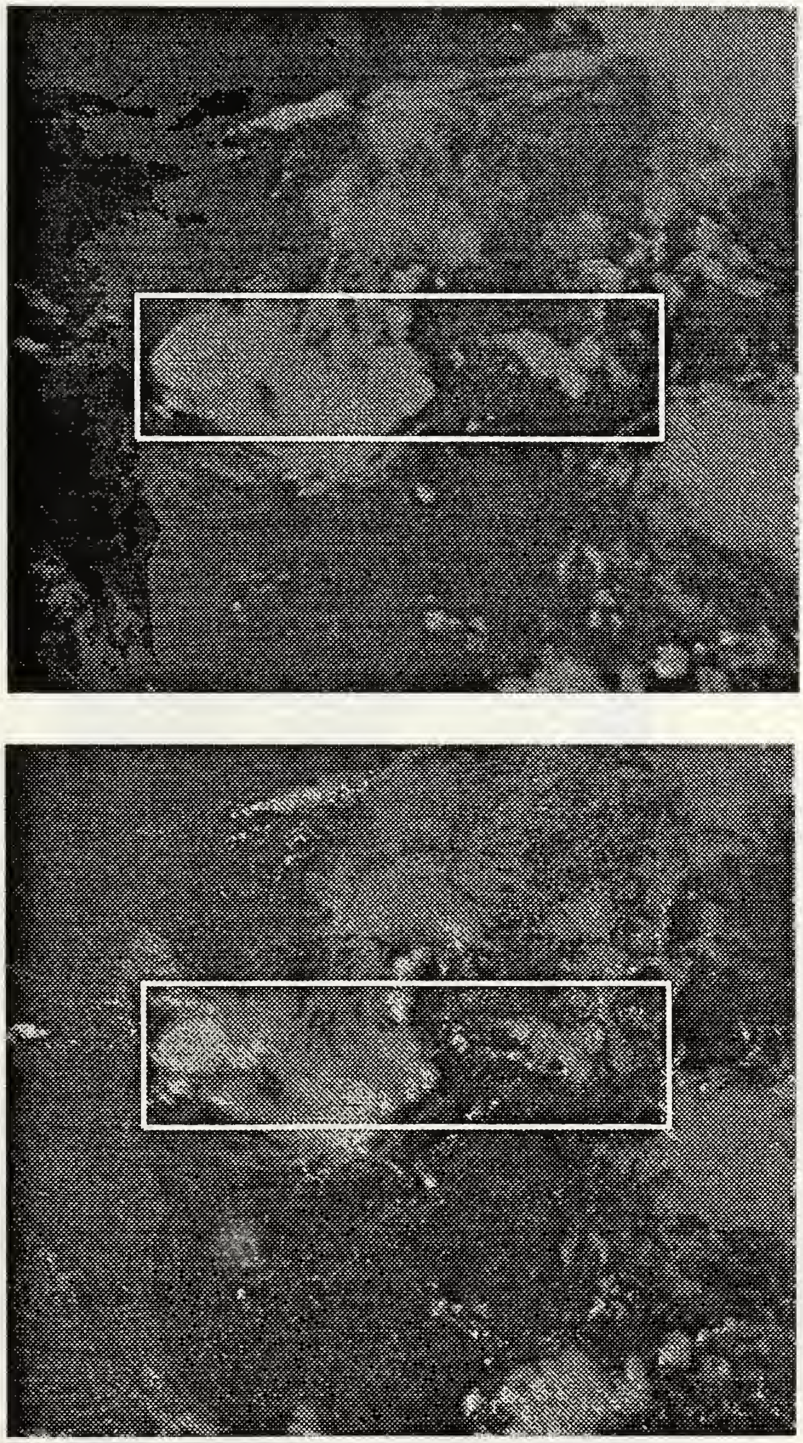


Figure 19 Sectors of GOES IR (a) and visible (b) images covering the Gulf Coast region at 2101 UTC 3 September 1992. Area to be displayed in 3–D indicated by box.

(a)

(b)

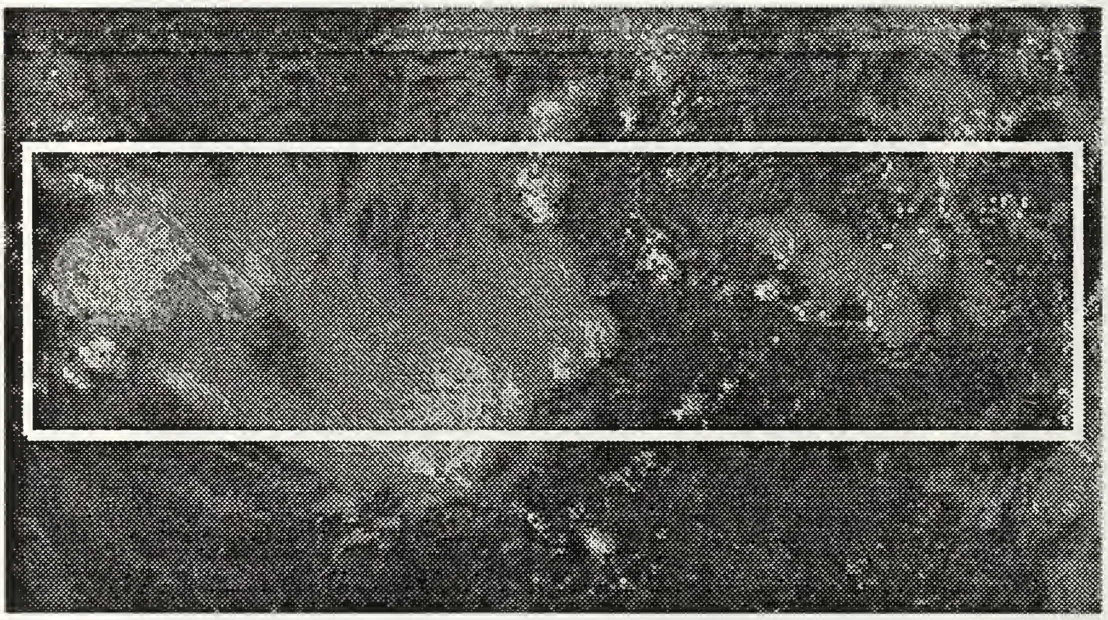


Figure 20 Enlarged views of the GOES IR (a) and visible (b) subimages covering the Gulf Coast region at 2101 UTC 3 September 1992. Area to be displayed in 3–D indicated by box.

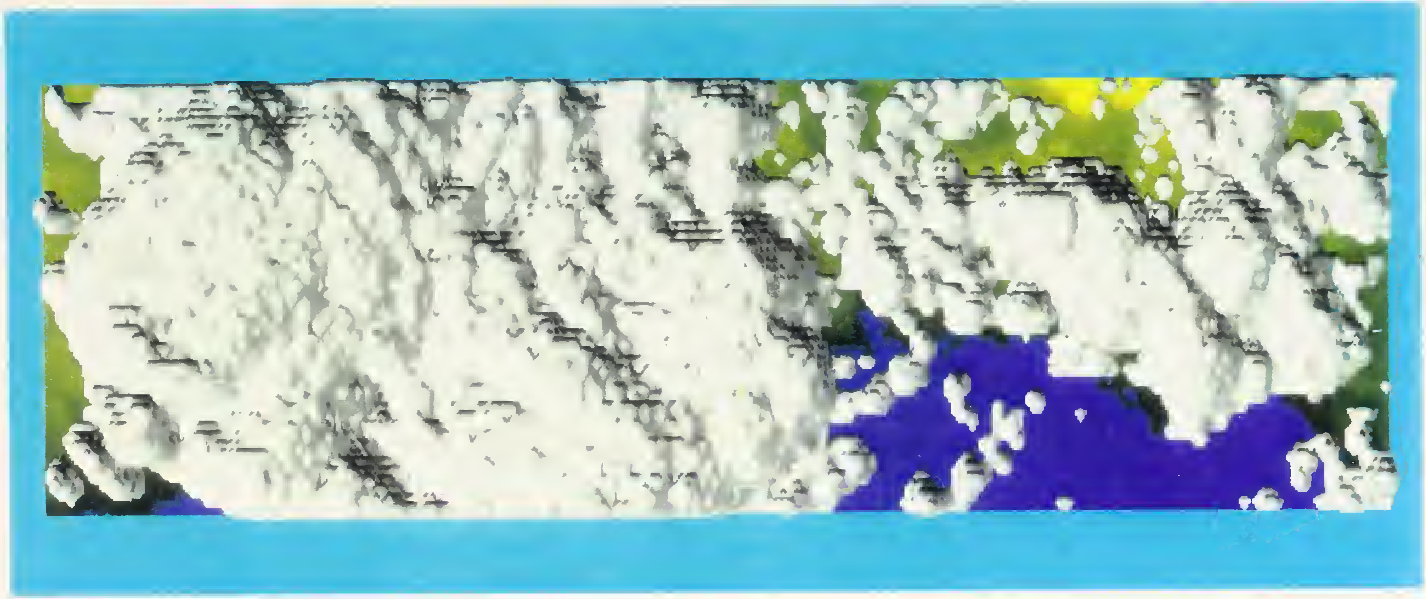


Figure 21 View from above of the 3–D rendering of cumulus cloud scene over Gulf Coast region on 3 September 1992.

outside of the area in the same location (northern Florida) as seen in the satellite images. Several strong cumulus cells are indicated over the right central portion of the image (the Florida panhandle). Isolated small cumulus are evident in the lower right portion of the image (northeast Gulf of Mexico), with much of the water not being obscured by clouds. The western half of the image (Louisiana and eastern Texas) is filled by large cloud masses. The southern edge of the cloud cell south of Louisiana has been cut off by the image boundary. The edge of the large cell over eastern Texas just fits within the western boundary of the image. The lower left and upper left corners show areas of no clouds or spotty small cumulus, which corresponds well to the satellite image. Overall, the 3-D rendering gives a representative picture, especially when comparing it to the visible satellite image.

Figure 22 displays the cloud scene after rotating the viewing perspective to a horizontal cross section view from the south. The flat wall of clouds seen in the left portion of the image is an artifact of the southern box boundary cutting through the center of the cloud mass in the satellite image. This cross sectional view displays the varying cloud bases very well. The bases near the right portion of the screen are low, increasing to the west (over the Florida panhandle), then decreasing under the massive cloud to the

Figure 22 Ground level view from the south of the 3–D rendering of cumulus cloud scene over Gulf Coast region on 3 September 1992.

west (south of Louisiana) and increasing again over the western most edge of the image (eastern Texas).

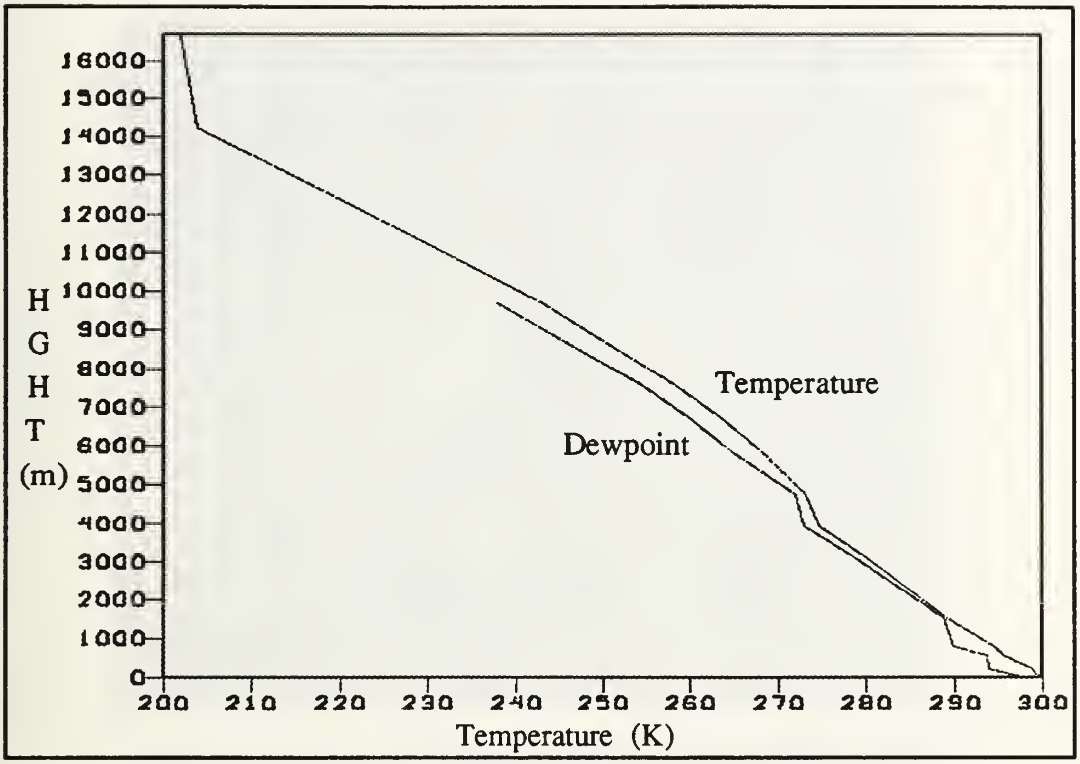
D. HURRICANE ANDREW

The final case depicts Hurricane Andrew as it crossed southern Florida during early morning on 24 August 1992. The West Palm Beach sounding at 1200 UTC 24 August 1992 (Figure 23a) indicates a very moist atmosphere at all levels under 10000 m. The temperature below 16000 m retains a positive lapse rate, simplifying the IR temperature to cloud top height conversion as in the cumulus cloud case. A plot of surface observations of low cloud bases at 1200 UTC (Figure 23b) show only several observations across the Florida peninsula. Since most of the area of interest is void of cloud base information, the cloud bases for this case were set to a constant height of 500 m.

The GOES IR and visible images at 1201 UTC 24 August 1992 (Figure 24) contain an area of interest that encompasses most of the clouds associated with Hurricane Andrew as it crossed southern Florida. Figure 25 shows enlarged views of the boxed areas from Figure 26. Andrew's eye is barely distinguishable near the center of the box. Distinct cloud bands are evident in a spiral pattern around the eye. The upper right and lower left box corners indicate little to no clouds.

The 3-D rendering of Hurricane Andrew (Figure 26) is displayed with a X direction distance of 473 km and a Y

(a)



(b)

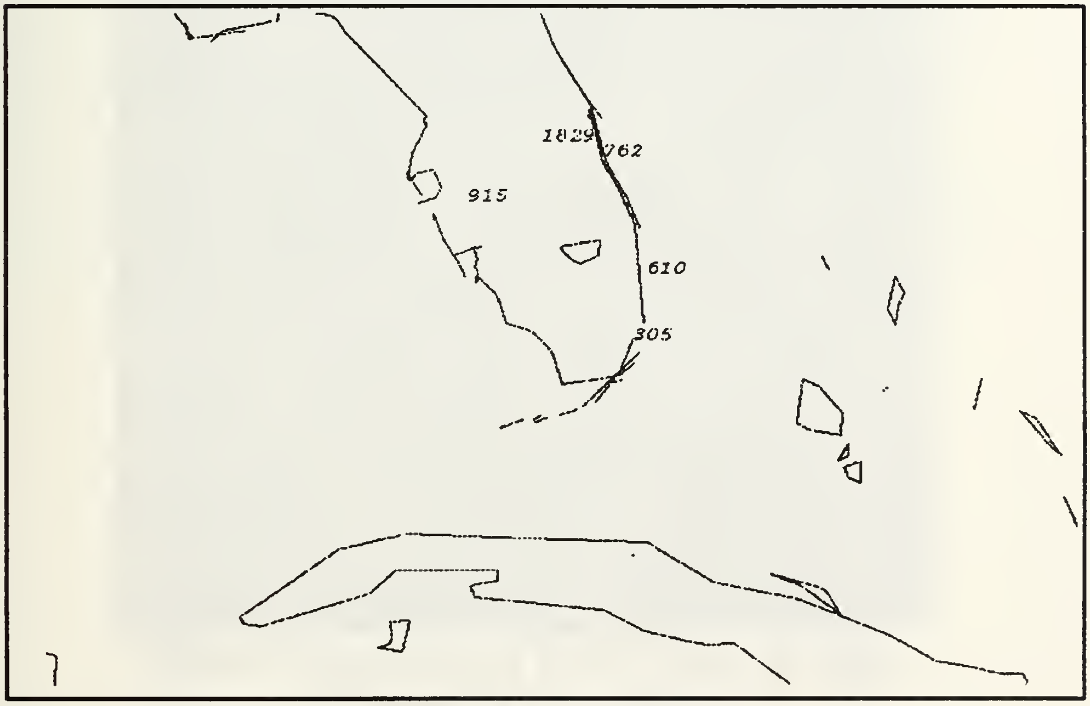
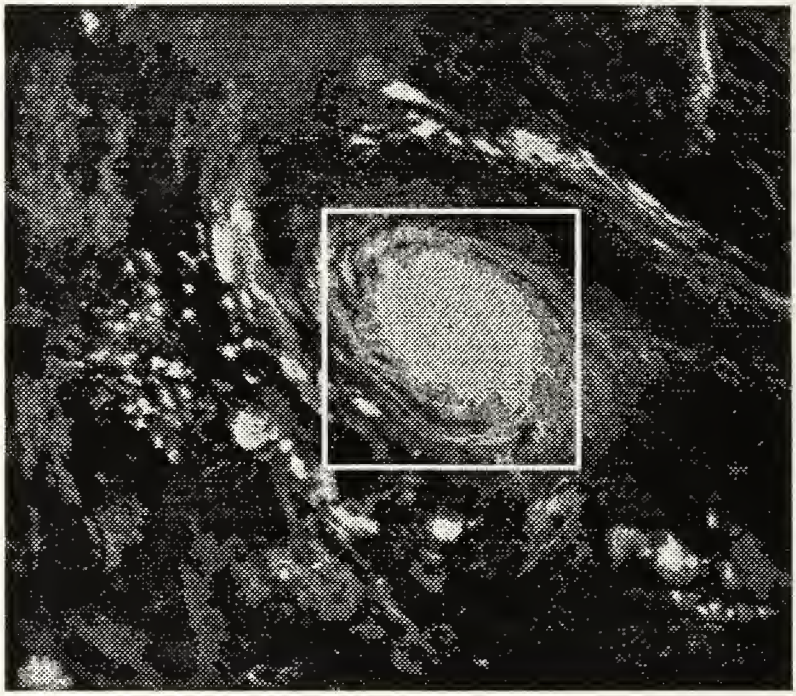


Figure 23 GEMPAK plots of West Palm Beach sounding data at 1200 UTC 24 August 1992 (a) and observed low cloud bases (m) at the same time (b).

(a)



(b)

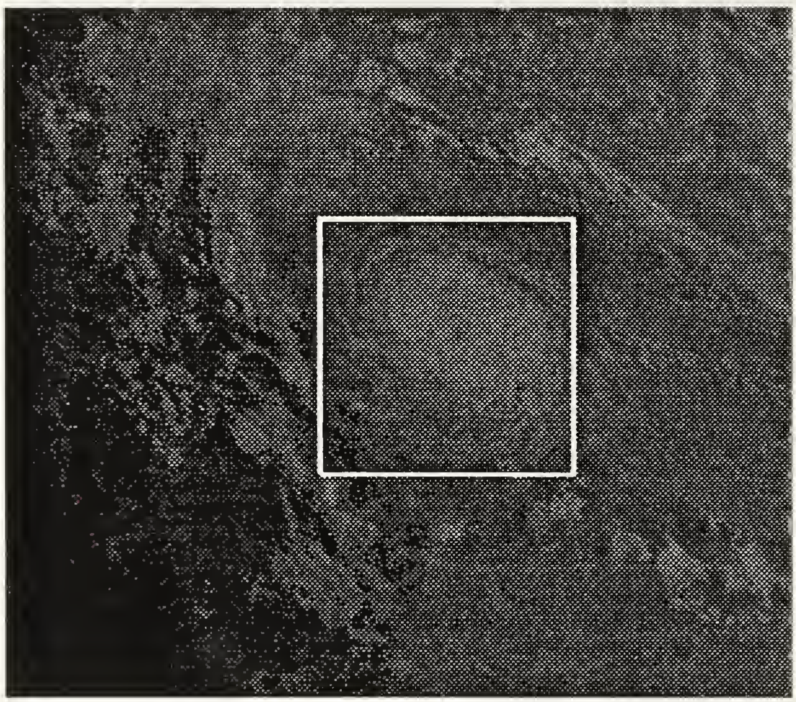
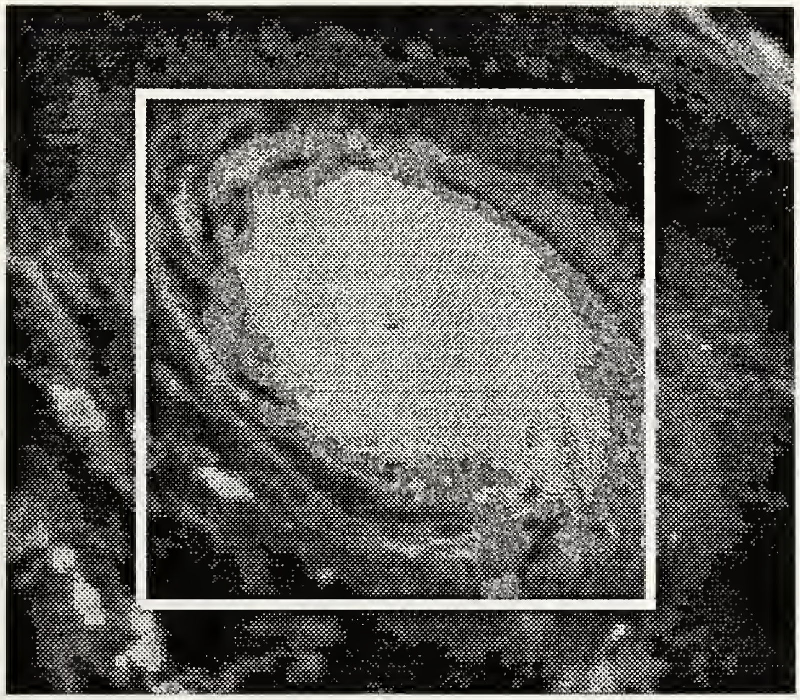


Figure 24 Sectors of GOES IR (a) and visible (b) images of the southeast U.S. at 1201 UTC 24 August 1992. Area to be displayed in 3–D indicated by box.

(a)



(b)

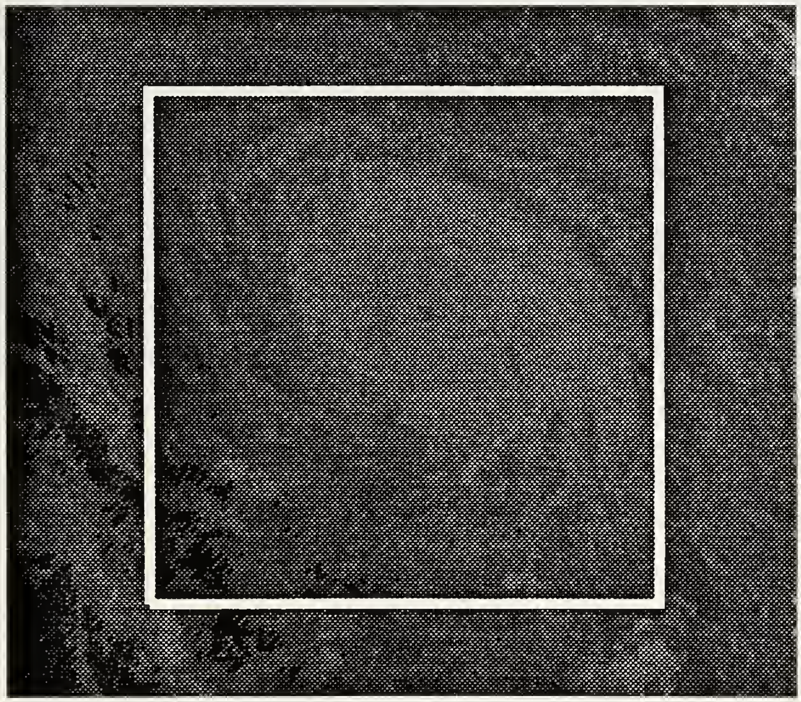


Figure 25 Enlarged views of the GOES IR (a) and visible (b) subimages of Hurricane Andrew at 1201 UTC 24 August 1992. Area to be displayed in 3–D indicated by box.

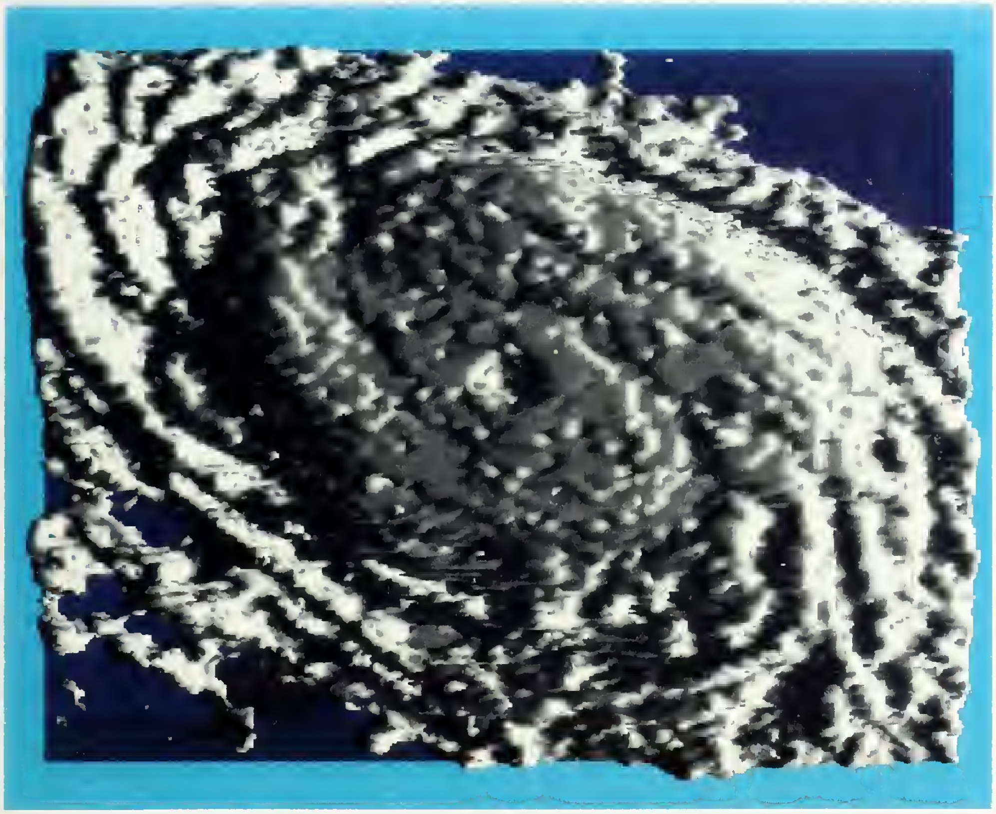


Figure 26 View from above of the 3–D rendering of Hurricane Andrew over southern Florida on 24 August 1992.

direction distance of 371 km. Portions of northern Cuba are evident in the southern most part of the image. The Florida peninsula is completely obscured by clouds from this viewing angle. Andrew's eye is evident near the center of the image with spiraling cloud bands surrounding the eye. The upper right and lower left corners are areas of little to no clouds.

Figure 27 shows the hurricane cloud scene from a tilted and zoomed in perspective from the east. The sun angle is shining directly towards the cloud scene at approximately the same angle that the viewing eye is placed. The tops of the cloud bands throughout the image vary tremendously, displaying definition that is not recognizable in the IR image alone. Most of the cloud tops close to the eye region are close to the same height, although isolated protruding tops are observed to the north and east of the eye.

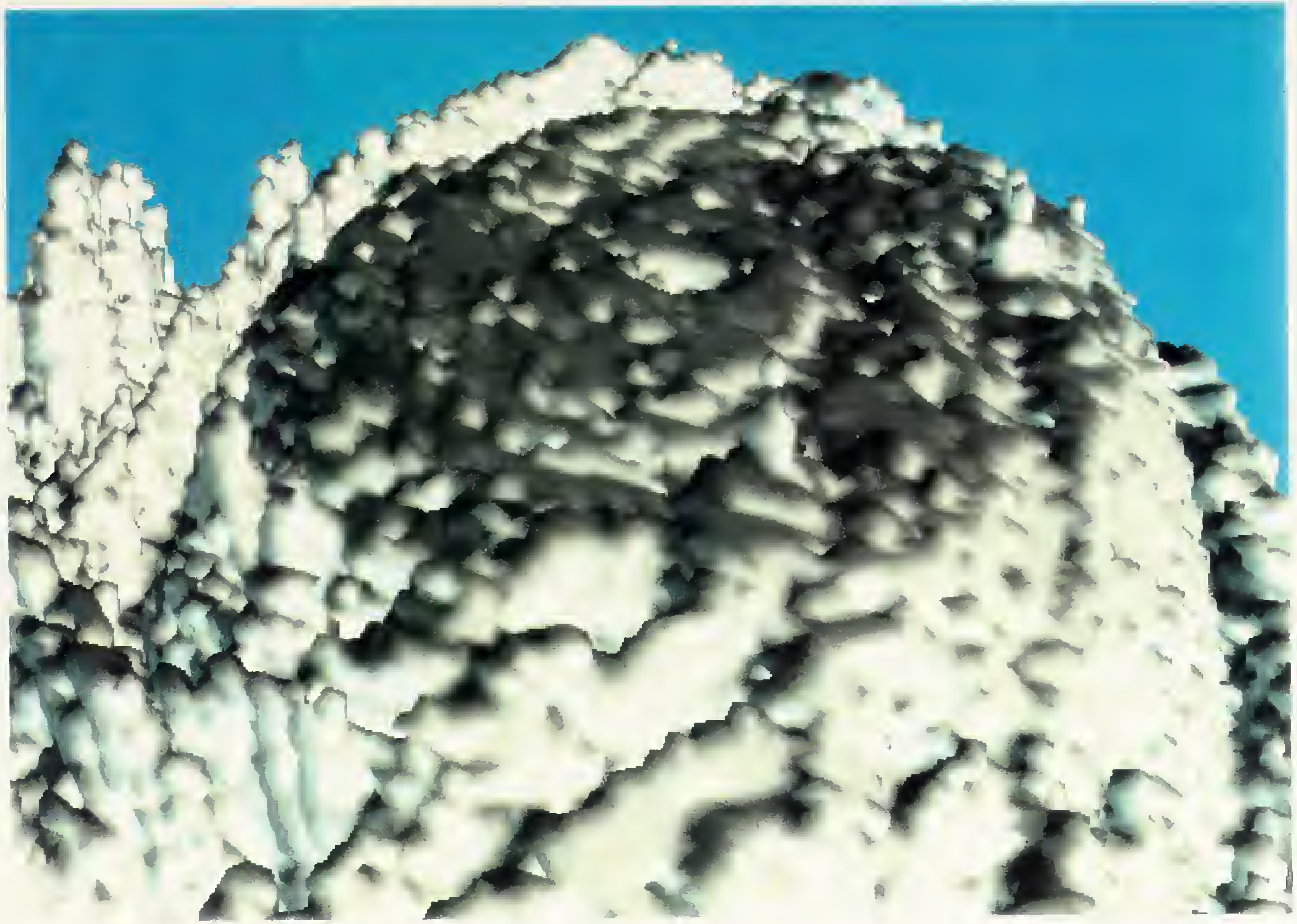


Figure 27 Tilted and zoomed in view from the east of the 3–D rendering of Hurricane Andrew on 24 August 1992.

V. CONCLUSION

A. SUMMARY

Effective visualization of large scientific data sets can now be accomplished efficiently due to recent computer graphics advancements. Visualization software employed on high performance graphics workstations offer new insight to traditional meteorological data. "Real time" user interaction with 3-D visualizations of data creates an almost life like environment where data relationships can be studied in realistic recreations of actual occurrences.

Information from satellite imagery, upper air sounding data, surface weather observations and topography data have been combined to construct 3-D cloud scenes with varying terrain, cloud tops and cloud bases. Using the SciAn visualization package, user interaction with the cloud scenes was in "real time" and included zoom transformations, rotations and flight simulation "fly-bys".

Three dimensional cloud scenes of various cloud types have been constructed and studied. One case, comprised of low stratus clouds off of the California coast, allowed for study of the clouds' relationship with terrain. A second case involved low stratus clouds and high clouds over the western Great Plains and the Rocky Mountains. Summertime convective

cumulus across the Gulf Coast comprised a more complex vertical structure case. The final case was a recreation of Hurricane Andrew as it crossed southern Florida. "Real time" interaction with the 3-D cloud scenes helped determine location and vertical extent of clouds that can not be done with traditional analysis techniques.

B. FUTURE WORK

The use of the GOES satellite data and the ETOPO5 topography data showed that cloud and terrain information can be combined to recreate realistic scenes. However, the resolution inherent to each of these data sets prevents the scenes from having realistic vertical scales. Future work with AVHRR satellite data or other high resolution satellite imagery, and higher resolution topography data holds promise for displaying the scenes with real vertical scales.

Cloud classification from IR and visible reflectivity data has been demonstrated with some success (Wash, et al., 1985). The implementation of satellite cloud classification techniques would help determine the types of clouds in the cloud scene and provide needed information for high cloud bases. In addition, a better randomization of cloud filling below cloud tops is desired for cumulus construction. Future work with fractal simulations of cumulus may help in this area.

While the visualization package used for this work was not capable of time sequence animation of the 3-D renderings, preliminary procedures were developed to animate a series of 3-D images. These procedures included constructing the 3-D cloud scenes as described within this thesis, saving the constructed cloud scenes to image files, then implementing digital video equipment to play back the sequence of images. To smooth the jerky motion associated with looping hourly data, ten minute linear interpolation of the extracted IR temperature data was performed. The resulting animation is included in the video tape of cloud scene interaction (Appendix B). Future work in this area should focus on more appropriate interpolation schemes, such as object recognition and transformation instead of linear interpolation of the IR temperature data. Other visualization software may also offer better capabilities for time animation then what is currently available with SciAn. A visualization package that allowed "fly-by" type investigation within a moving time sequence would construct more realistic recreations of actual atmospheric occurrences.

APPENDIX A

PROGRAMS FOR CONSTRUCTING 3-D CLOUD SCENES

TEMPEXT - Extract IR temperatures from box area on GOES or AVHRR IR image.
FORTRAN program used on VAX system.
Author: Kurt Nielsen, June 1992, NPS.

TERRAIN - Extract topography data from ETOPO5 data.
FORTRAN program used on VAX system.
Author: Jim Cowie, February 1990, NPS.
C program conversion used on SGI system.
Author: Kevin Stone, December 1992, NPS.

SUNANGLES - Calculate solar zenith and azimuth angles given date/time and latitude/longitude of location.
C program used on SGI system:
Author: Kevin Stone, December 1992, NPS.
Converted from FORTRAN program by Rick Kohrs, Doug Burks, Craig Motell and Lang Chou, July 1988, NPS.

3DCLOUDS - Construct 3-D cloud arrays and 2-D terrain arrays in correct format for SciAn to read.
C program used on SGI system.
Author: Kevin Stone, December 1992, NPS.

SCIAN - Version 0.57. Visualize and animate multi-dimensional scientific data sets.
C program used on SGI system.
Author: Eric Pepke, Jim Murray, John Lyons, August 1992, Florida State University.

APPENDIX B

VIDEO TAPE OF CLOUD SCENE INTERACTIONS

Interactions with the four cloud cases have been recorded to video tape. The tape is 30 minutes in length, including 15 minutes of a presentation slideshow. The interactions include rotations, zoom transformations, and "fly-bys" in and around the cloud scenes.

If interested in obtaining a copy of this video tape contact:

Prof C. Wash
Code MR/Wx
or
Prof P. Durkee
Code MR/De
at:
Naval Postgraduate School
Monterey, CA 93943-5000

Network access on OMNET:
C.WASH or P.DURKEE

Or on INTERNET:
Wash@lady.met.nps.navy.mil
Durkee@lady.met.nps.navy.mil

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